Advances in Agronomy

Volume 91





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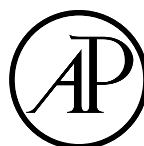


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ISBN-13: 978-0-12-000809-4
ISBN-10: 0-12-000809-2

PRINTED IN THE UNITED STATES OF AMERICA
06 07 08 09 9 8 7 6 5 4 3 2 1

Contents

GEOCHEMICAL ASPECTS OF PHYTOSIDEROPHORE-PROMOTED IRON ACQUISITION BY PLANTS

S. M. Kraemer, D. E. Crowley and R. Kretzschmar

Taking Stock of the Brazilian "Zero-Till Revolution": A Review of Landmark Research and Farmers' Practice

Adrian Bolliger, Jakob Magid, Telmo Jorge Carneiro Amado, Francisco Skóra Neto, Maria de Fatima dos Santos Ribeiro, Ademir Calegari, Ricardo Ralisch and Andreas de Neergaard

Mechanisms and Pathways of Trace Element Mobility in Soils

R. Carrillo-González, Jirka Šimůnek, Sébastien Sauvé and Domy Adriano

The Agronomy and Economy of Cardamom (*Elettaria cardamomum* M.): The "Queen of Spices"

K. P. Prabhakaran Nair

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Preface

Volume 91 contains four comprehensive reviews on agronomic topics. Chapter 1 is a timely overview on the phytosiderophase promoted iron acquisition by plants. Chapter 2 is an interesting review on the growing importance of zero tillage in Brazil. Chapter 3 deals with a worldwide environmental issue, trace element mobility in soils. Chapter 4 is a comprehensive review on cardamom, including production and management and medicinal and food uses.

I appreciate the excellent contributions of the authors.

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Geochemical Aspects of Phytosiderophore-Promoted Iron Acquisition by Plants

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Iron is an essential trace nutrient for all plants. The acquisition of iron is limited by low solubilities and slow dissolution rates of iron-bearing minerals in many soils. Therefore, iron limitation can be an important nutritional disorder in crop plants, leading to decreased yields or significant costs for iron fertilization. However, some species among the group of graminaceous plants (including wheat and barley) exhibit a rather low susceptibility to iron deficiency. These species respond to iron-limiting conditions by the exudation

Advances in Agronomy, Volume 91

0065-2113/06 $35.00
DOI: 10.1016/S0065-2113(06)91001-3

of ligands with a high affinity and specificity for iron complexation, the so-called phytosiderophores. Soluble iron–phytosiderophore complexes are recognized and transported across the root plasma membrane by specific transport proteins. This chapter focuses on geochemical aspects of this so-called "strategy II" iron acquisition mechanism. The coordination chemistry of phytosiderophores and their iron complexes in the soil solution are discussed and compared to other organic ligands including low-molecular weight organic acids and microbial siderophores. The properties of iron complexes and iron-bearing minerals in the rhizosphere are discussed and compared with regard to their potential as sources of plant available iron. An important focus of this chapter is the elucidation of the thermodynamics, mechanisms, and rates of iron acquisition from these sources by phytosiderophores. Thus, we hope to contribute to the understanding of iron acquisition by strategy II plants in particular and of iron cycling in the rhizosphere in general.

ABBREVIATIONS

DA-A	distichonic acid A
DDA-A	deoxydistichonic acid
DFO-B	desferrioxamine B
DFO-D1	desferrioxamine D1
DMA	deoxymugienic acid
DOM	dissolved organic matter
DTPA	diethylenetriaminepentaacetic acid
EDTA	ethylenediaminetetraacetic acid
3-epiHMA	3-epihydroxymugineic acid
EXAFS	X-ray adsorption fine structure spectroscopy
HMA	hydroxymugienic acid
HBED	*N,N*-di(2-hydroxybenzoyl)-ethylenediamine-*N,N*-diacetic acid
HEDTA	*N*-(2-hydroxyethyl)ethylenediamine-*N,N′,N′*-triacetic acid
HS	humic substance
MA	mugienic acid
Mi	uptake-rate controlling metal species
NA	nicotianamine
NHE	norman hydrogen electrode
NOM	natural organic matter
PS	phytosiderophore

I. INTRODUCTION

Iron is a trace nutrient that serves many functions in plant biochemistry due to its central role as electron donor or acceptor in enzymes. The acquisition of iron is therefore a matter of survival for plants as well as for most other known eukaryotic and prokaryotic organisms. Plants are usually well adapted to the specific nutrient availabilities in their natural habitats. However, crop plants are often grown in soils where their ability to acquire iron is insufficient to overcome the low iron availability that is characteristic of the substrate. The costs associated with controlling iron deficiency in crops under these conditions are significant. For example, it has been estimated that the annual costs for iron deficiency control are as high as €80–100 million in the Mediterranean area (Abadía *et al.*, 2004) and $120 million in the soybean-growing areas of the North Central United States (Hansen *et al.*, 2004). However, not all crops suffer the same problem. For example, it was found that some crop-relevant species among the group of graminaceous plants (e.g., barley and wheat) were less susceptible to iron deficiency than other nongraminaceous species (Römheld and Marschner, 1986). This chapter adresses geochemical processes that are involved in efficient iron acquisition by such plants. The properties of soils that promote iron deficiency are introduced, and the biogeochemical interactions of plant roots with the soil that alleviate iron deficiency are discussed. A focus of this chapter is iron acquisition processes involving the exudation of phytosiderophores by plant roots.

Plant roots dramatically modify the chemical environment of the rhizosphere and thereby influence processes such as mineral weathering and the mobility of nutrients and pollutants. The prediction of the impact of complex and dynamic root physiological processes on soil chemistry is thus a major challenge for biogeochemical research. Ideally, the rewards of this research include a better understanding of plant nutrient acquisition, pollutant transport, and mineral-weathering processes. An understanding of these processes must first consider the chemical substances that are released into the rhizosphere, the modification of these substances by microorganisms, and the interactions of organic acids and other ligands in the dissolution of various minerals. Among the different elements that are required by plants, the release of organic acids and chelating substances from the plant root is of particular importance for solubilization of iron and zinc, which are the most commonly limiting trace elements in alkaline soils that comprise about one-third of the world's land surface area. To overcome iron limitation, graminaceous plants release substances called phytosiderophores that are soluble organic ligands with a high affinity for iron.

The geochemistry of iron in the rhizosphere is a "ground-truth" that any iron acquisition strategy has to address. Some of the key problems that need to be overcome to supply iron to a root are related to the following:

The low solubility of iron-bearing mineral phases.
Their slow dissolution kinetics.
The transport of soluble iron species to the root.
The low bioavailability of certain soluble iron complexes.
Slow iron release from these complexes in ligand- or metal-exchange reactions.

Some of these problems are interrelated, and root responses to iron deficiency may act on several of the factors listed earlier. Also, it is important to explore synergisms and antagonisms between various known root activities. Ultimately, iron acquisition or any biogeochemical interaction is a complex optimization problem that may have more than one solution leading to the desired result: survival!

II. STRATEGIES OF PLANT IRON ACQUISITION

A. Strategy I

Plant roots respond to iron deficiency by various morphological and physiological changes. A range of plants improve iron acquisition by enhancement of H^+ efflux via a proton ATPase and the exudation of reductants and ligands, as well as enzymatic iron reduction by plasma membrane-bound reductases. The uptake of Fe(II) is facilitated by an inducible Fe(II) transporter (Grotz and Guerinot, 2003). This iron acquisition strategy is referred to as "strategy I" (Marschner *et al.*, 1986b).

Iron mobilization by proton efflux into the rhizosphere takes advantage of the effect of soil solution pH on iron solubility. However, in calcareous soils the pH is buffered by heterogeneous reactions with the CO_2 in the gas phase and calcite. The atmospheric CO_2 partial pressure is about $10^{-3.5}$ atm. Much higher CO_2 partial pressures ($10^{-1.2}$ to $10^{-0.9}$ atm) have been observed in the rhizosphere due to high respiration rates by plant roots and microorganisms (Gollany *et al.*, 1993). This influences the pH and the solubility of iron and calcium as illustrated in Fig. 1.

The pH of a soil solution in equilibrium with calcite decreases from 8.3 at atmospheric P_{CO_2} to pH 6.8 at a rhizospheric P_{CO_2} of $10^{-1.2}$ atm while the soluble calcium concentration increases from 0.6 to 3.4 mM. The total concentration of soluble inorganic iron species at this rhizospheric P_{CO_2} in equilibrium with "soil iron oxide" (Lindsay and Schwab, 1982) is only 2 nM.

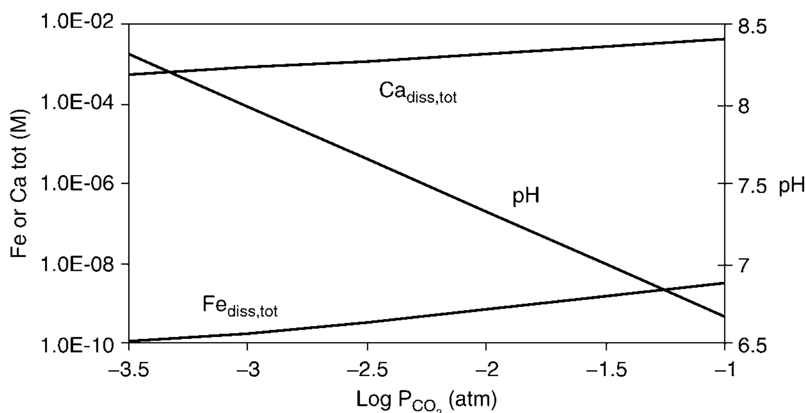


Figure 1 Calculated pH and total concentrations of dissolved inorganic Ca and Fe species as a function of the CO_2 partial pressure in equilibrium with calcite and "soil iron oxide" (Lindsay and Schwab, 1982). All solubility coefficients and equilibrium constants listed in Tables IV and V.

Various strategy-I plant species of the Proteaceae, Casuarinaceae, Mimosadeae, Fabaceae (e.g., *Lupinus albus*), Myricaceae, and Moraceae families respond to nutrient limitations by forming cluster (i.e., proteoid) roots that are particularly efficient in modifying rhizosphere pH and organic acid concentrations (Dinkelaker *et al.*, 1995; Neumann and Martinoia, 2002). Cluster root formation has been observed as a response to phosphorus (Dinkelaker *et al.*, 1995) and iron (Arahou and Diem, 1996; Gardner *et al.*, 1982; Waters and Blevins, 2000; White and Robson, 1989) limitations.

Strategy I plants promote the release of iron from organic complexes by enzymatic reduction via membrane-bound chelate reductases of rhizodermal cells (Bienfait, 1985; Chaney *et al.*, 1972; Robinson *et al.*, 1999; Waters *et al.*, 2002). The reduction of iron in soluble complexes leads to the kinetic and thermodynamic labilization of iron and facilitates its uptake (Marschner, 1995). For in-depth discussions of the role of membrane-bound reductases in root iron uptake, the reader is referred to a number of reviews and textbooks (Berczi and Moller, 2000; Curie and Briat, 2003; Hell and Stephan, 2003; Marschner, 1995; Schmidt, 1999, 2003).

B. Strategy II

Graminaceous plant species, including agriculturally important crops, such as barley, wheat, and corn, respond to iron deficiency by exudation of iron-specific organic ligands, the so-called phytosiderophores (Takagi, 1976;

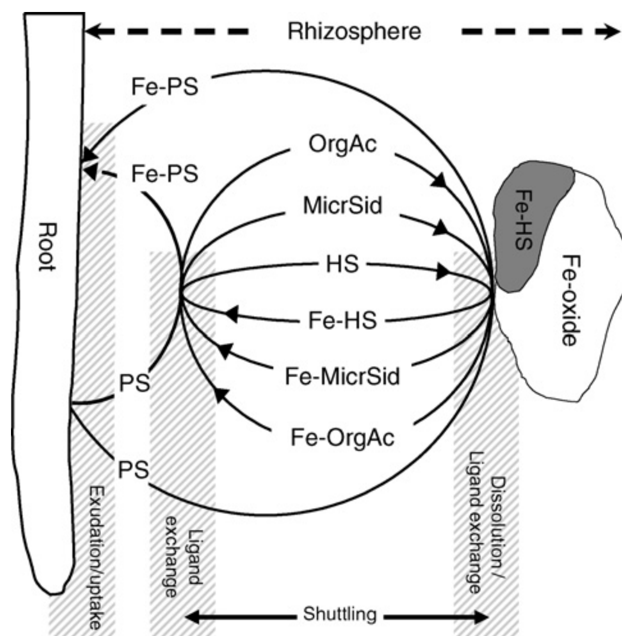


Figure 2 Schematic representation of important processes in strategy II iron acquisition (not to scale). PS, phytosiderophores; OrgAc, low-molecular weight organic acids; MicrSid, bacterial and fungal siderophores; HS, soluble particulate, or sorbed humic and fulvic substance.

Takagi *et al.*, 1984). The resistance of graminaceous species to iron deficiency is correlated to their phytosiderophore release rates (Römheld and Marschner, 1990). In the apoplastic space and the rhizosphere, phytosiderophores can scavenge iron from a range of iron-bearing compounds including iron oxides (Fig. 2).

The iron deficiency induced synthesis and exudation of phytosiderophores, and the subsequent uptake of iron–siderophore complexes has been described as the "strategy II" iron acquisition mechanism (Marschner *et al.*, 1986b). This strategy resembles bacterial and fungal iron acquisition systems involving microbial siderophores. A large body of work has been devoted to the regulation and molecular level understanding of the plant physiological responses to iron deficiency. We refer the reader to a number of excellent review and textbooks for detailed information on these subjects (Curie and Briat, 2003; Grotz and Guerinot, 2003; Reid and Hayes, 2003; Schmidt, 2003). This chapter focuses on the geochemical aspects of strategy II iron acquisition.

III. HOW MUCH IS ENOUGH? PLANT IRON REQUIREMENTS

Iron is a constituent of a number of plant enzymes such as heme proteins (including cytochromes, catalases, and peroxidases), iron–sulfur proteins (including ferredoxin, superoxide dismutase, and aconitase), lipoxygenase, and so on (Marschner, 1995). Considering the array of functions of iron-bearing enzymes, it is not surprising that iron limitation has a range of consequences including the impairment of various metabolic and biosynthetic functions and of photosynthesis (Abadia, 1992; Marschner, 1995). The resulting deficiency syndrome is iron-deficiency chlorosis. The minimum total iron content of iron-sufficient plant leaves is in the range of 50–150 mg kg^{-1} dry weight (Marschner, 1995).

The speciation of iron in the rhizosphere has an important effect on iron-uptake rates. Hydroponic culture experiments have been very important to investigate this effect and to establish free ion activity models (FIAM) in which uptake rates (V) can be related to the activity of a rate-controlling metal species $\{M_i\}$ (Hudson, 1998):

$$V = f(\text{organism, chemical environment, physical environment}, \{M_i\})$$

The rate-controlling iron species is understood as the species, that is directly taken up by the plant root with the highest uptake rate compared to other species in the following reaction:



$$M_i + X \leftrightarrow MX \quad (1)$$



$$MX \rightarrow M_{cellular} \quad (2)$$

where X is the receptor for M_i of the uptake system at the cell surface. Generally, it is assumed that M_i is the metal aquo complex (the "free ion") (Chaney *et al.*, 1992; Morel and Hering, 1993; Parker and Norvell, 1999). The activity of M_i is usually calculated by equilibrium models rather than measured, due to the inherent difficulty to measure individual species. The FIAM is based on the assumption that an equilibrium exists between M_i, all other species in solution, and the binding sites of the transporter at the cell surface (Hudson and Morel, 1990). The application of the FIAM to total plant uptake requires that there is no indiscriminate uptake of complexes via breaks of the Casparian strip etc. However, evidence of such direct uptake pathways of natural and synthetic ligand complexes exists (Bell *et al.*, 2003, 2005a; Wang *et al.*, 1993). Further complications arise if chelators of the metal ion are toxic to plants (Rengel, 1999, 2002). Some excellent reviews and textbooks

Table I
Iron Requirements of Various Plant Species Grown in Hydroponic Culture

Plant species	Ligand	$[Fe]_{tot}$[a] [M]	Assumed M_i[b]	$\{M_i\}$[c] [M]	References
Barley	HEDTA[d]	6×10^{-6}	Fe^{3+}	10^{-18}	Bell *et al.*, 1991
	EDTA[e]	9×10^{-6}		10^{-19}	
Barley	HBED[f]	10×10^{-6}	Fe^{3+}	$10^{-14.1}$	Bell *et al.*, 2005b
Tomato, soybean	DTPA[g]	?	Fe^{3+}	10^{-28}	Chaney *et al.*, 1988
Soybean	–	0.1×10^{-6}	Fe^{2+}	10^{-7}	Lindsay and Schwab, 1982
Barley	HEDTA	7.5×10^{-6}	Fe^{3+}	$10^{-17.5}$	Gries *et al.*, 1995

[a]$[Fe]_{tot}$: Total soluble iron concentration in the nutrient solution.
[b]M_i: The rate controlling metal species, here free aquocomplexes of Fe(III) or Fe(II).
[c]$\{M_i\}$: Activity of a rate-controlling metal species M_i.
[d]HEDTA: *N*-(2-Hydroxyethyl)ethylenediamine-*N,N′,N′*-triacetic acid.
[e]EDTA: Ethylenediaminetetraacetic acid.
[f]HBED: *N,N*-di(2-hydroxybenzoyl)-ethylenediamine-*N,N*-diacetic acid.
[g]DTPA: Diethylenetriaminepentaacetic acid.

discussing the FIAM are available (Campbell, 1995; Campbell *et al.*, 2002; Hudson, 1998; Morel and Hering, 1993; Parker and Norvell, 1999; Parker and Pedler, 1997).

The uptake of iron in strategy II plants proceeds via a high-affinity and a low-affinity uptake system (von Wirén *et al.*, 1995). The high-affinity system involves the enzymatic transport of intact Fe–phytosiderophore complexes through the plasma membrane by a transporter (Römheld and Marschner, 1986). This uptake system controls the rate of iron uptake under iron-limiting conditions. Therefore, it seems appropriate to assume that in this case $\{M_i\}$ is the activity of the Fe–phytosiderophore complex. Unless phytosiderophore concentrations are measured or added to the nutrient solution to a known level, their concentration is not known and $\{M_i\}$ cannot be calculated in equilibrium models. Their concentration in hydroponic culture experiments will be a function of exudation rates, degradation rates, and the volume of nutrient solution relative to the root biomass among other factors. In the rhizosphere, siderophore concentrations are influenced by diffusional transport away from the root and advective transport to the root. During maximum exudation periods, local siderophore concentrations can reach very high levels as discussed later (Römheld, 1991). Almost certainly, local rhizosphere concentrations will be very different from siderophore concentrations in well-mixed hydroponic culture experiments. Nevertheless, iron-limiting conditions are usually defined as the maximum activity or concentration of the iron hexaquo complex (i.e., "Fe^{3+}") at which iron deficiency chlorosis occurs (see Table I).

The rate of enzymatic high-affinity uptake of iron–siderophore complexes can be described by a Michaelis–Menten type rate law:

$$\rho = [M_i]\rho_{max}/K_M + [M_i] \quad (3)$$

where ρ is the uptake rate and ρ_{max} is the maximum uptake rate, $[M_i]$ is a Fe–siderophore complex, and K_M is the half saturation constant. The uptake rate is linearly related to $[M_i]$ at low concentrations of M_i ($[M_i] < K_M$). At high concentrations ($[M_i] < K_M$), the uptake rate saturates, that is, it becomes independent of $[M_i]$ and $\rho = \rho_{max}$ (Morel and Hering, 1993). Von Wirén *et al.* (1995) measured a K_M of 10 μM Fe–DMA and $\rho_{max} = 5.5$ μmole Fe per g (dry weight) per 30 min for the iron efficient *Z. mays* L. cv. Alice. Observations of uptake kinetics of Fe–DMA with isolated root plasma membrane vesicles of the same cultivar were fitted to a Michaelis–Menten model with K_M of 0.6 Fe–DMA and $\rho_{max} = 5.5$ μM Fe min^{-1} mg^{-1} protein. These observations give an upper limit for Fe–phytosiderophore complex concentrations that will increase uptake rates via a fast uptake system in the range of 10^{-6} to 10^{-5} M.

IV. IRON-BEARING MINERALS AND SOLUBLE IRON SPECIES IN THE RHIZOSPHERE

Phytosiderophores can scavenge iron from a range of iron-bearing minerals and soluble iron species. The ultimate sources of iron in soils are primary iron-bearing minerals. Most iron-bearing primary minerals are not stable over pedological timescales. Iron liberated by weathering of primary minerals in well-aerated soils forms secondary iron oxide minerals and is bound to natural organic matter (NOM). Iron oxides control the activity of the iron–hexaquo complex by solubility equilibria and the activity of iron hydrolysis species by coupled equilibria. The low solubility of iron oxides in the neutral pH range is responsible for low dissolved iron concentrations that induce iron-deficiency symptoms in many plant species. However, the solubility of iron in soil solution is not only determined by hydrolysis species. Soluble organic ligands, including organic acids, polyphenols, fulvic and humic acids, and bacterial or fungal siderophores, can significantly increase iron solubility. Organic iron complexation does not increase the concentration of Fe^{3+} and hydrolysis species if the system is at equilibrium. However, some of the important biogeochemical reactions involved in iron acquisition are slow (e.g., the dissolution reaction) and it is unlikely that soluble iron concentrations in the rhizosphere are controlled by equilibria. In this case, soluble complexes may be important as iron sources and iron shuttles for strategy I and strategy II iron acquisition. Generally, it is useful to consider most of the solid or soluble iron species that will be

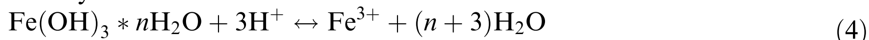
discussed here as intermediates of the complex chemical transformations that take place before iron is taken up by plant roots.

A. Iron-Bearing Minerals, the Penultimate Iron Source

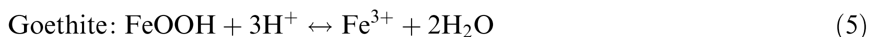
1. Mineral Structures and Solubilities

The weathering of iron-bearing primary minerals leads to the formation of secondary iron oxides. In most soils, iron oxides are the largest pool of iron. The iron content of aerated soils is in the range of 0.2–5% (Blume *et al.*, 2002), which is in the same range as the average crustal abundance of iron (3.5%) (Taylor, 1964). Important iron oxide minerals in soils are ferrihydrite, goethite (α-FeOOH), and hematite (α-Fe_2O_3). Ferrihydrite is a poorly ordered phase with variable composition (Cornell and Schwertmann, 2003). We report dissolution reactions and corresponding solubility constants based on the simplifying assumption of an $Fe(OH)_3 \cdot nH_2O$ stoichiometry. Based on observations of iron solubility in soils, Lindsay (1979) defined a hypothetical "soil iron oxide" that (Cornell and Schwertmann, 2003) interpreted as an aged ferrihydrite. The solubility of these minerals is expressed in terms of a solubility product and coupled hydrolysis reactions in solution. The dissolution reactions for these iron oxides are as follows:

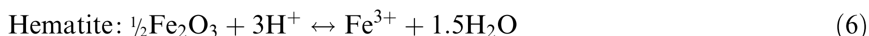
Ferrihydrite or "soil iron oxide":



$$Fe(OH)_3 * nH_2O + 3H^+ \leftrightarrow Fe^{3+} + (n+3)H_2O \quad (4)$$



$$\text{Goethite: } FeOOH + 3H^+ \leftrightarrow Fe^{3+} + 2H_2O \quad (5)$$



$$\text{Hematite: } \tfrac{1}{2}Fe_2O_3 + 3H^+ \leftrightarrow Fe^{3+} + 1.5H_2O \quad (6)$$

The solubility product for these reactions is:

$$K_s = \frac{\{Fe^{3+}\}}{\{H^+\}^3}$$

implying that the activity of the Fe^{3+} species in equilibrium with any of these iron oxides increases by a factor of 1000 for each unit decrease in pH. The solubility products depend on bulk lattice energies and particle sizes. Generally, ferrihydrite has a higher solubility product than the more crystalline goethite and hematite. However, the solubility products of goethite and hematite increase with decreasing particle size and approach the solubility product of ferrihydrite in the nanometer range (Langmuir, 1969; Trolard and Tardy, 1987). Goethite and hematite in the nanometer range are typically found in soils (Cornell and Schwertmann, 2003).

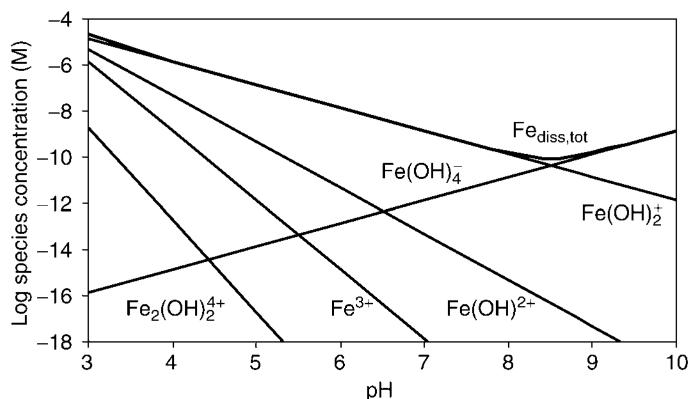


Figure 3 Calculated solubility of iron in equilibrium with "soil iron oxide" (Lindsay, 1979) and iron speciation as a function of pH. For solubility product constants and equilibrium constants for hydrolysis species, see Tables IV and V.

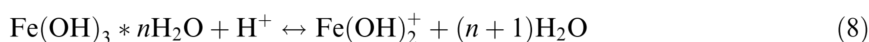
The solubility of iron, defined as the total dissolved iron concentration in equilibrium with a solid phase (IUPAC, 1997), is also determined by coupled hydrolysis equilibria as shown in Fig. 3.

The dominant hydrolysis species in the pH range between 6.5 and 7.5 is $Fe(OH)_2^-$. The formation of this species is given by Eq. (7) as follows:



$$Fe^{3+} + 2OH^- \leftrightarrow Fe(OH)_2^+ \tag{7}$$

Combining Eqs. (7) and (4), we can derive an expression for ferrihydrite dissolution in the neutral pH range:



$$Fe(OH)_3 * nH_2O + H^+ \leftrightarrow Fe(OH)_2^+ + (n+1)H_2O \tag{8}$$

with a modified solubility product:

$$K_{s'} = \frac{\{Fe(OH)_2^+\}}{\{H^+\}} \tag{9}$$

implying that the solubility of the iron oxides in this pH range increases by a factor of 10 for each decrease of pH by one unit (see also Fig. 1).

2. Surface Chemistry of Iron Oxides

Iron ions at iron oxide surfaces are coordinated by structural oxo- and hydroxo groups and by adsorbed water or hydroxyl groups. Net positive or negative surface charge arises primarily from protonation or deprotonation

of these coordinating groups at the mineral surface. Organic and inorganic ligands can adsorb at iron oxide surfaces by ligand exchange, that is, by replacement of adsorbed water or other ligands. This mode of adsorption leads to the formation of inner sphere surface complexes that can influence iron oxide dissolution mechanisms and rates as discussed later. The standard free energy change of the adsorption reactions includes contributions from the standard free energy change of the ligand-exchange reaction, of electrostatic interactions with the charged oxide surface, and of hydrophobic interactions. Charged ligands as well as metal ions can also adsorb by electrostatic interactions resulting in outer sphere complexation. If adsorbate and adsorbent have equal net charges, outer sphere complexation is not possible but inner sphere complexation is.

B. Iron Complexation by Organic Ligands

The formation of soluble iron complexes with organic ligands can strongly influence the solubility of iron in the rhizosphere. The magnitude of the effect of organic acids on iron solubility in soils that are buffered by free lime (calcium carbonate) depends on their concentration, affinity for iron complexation in solution, and tendency to form complexes with competing cations such as calcium. This is illustrated in Fig. 4 where the solubilities of "soil iron oxide" and goethite are plotted as a function of the soluble concentrations of various organic ligands at pH 6.8 in the presence and absence of calcite and at a P_{CO_2} of $10^{-1.2}$ atm. Desferrioxamine-B (DFO-B) is a microbial siderophore with extremely high affinity for iron. Essentially, all DFO-B is complexing iron in equilibrium with "soil iron oxide" or goethite in the absence and presence of soluble calcium. Citrate has a lower affinity for iron and consequently a lower effect on iron solubility. Moreover, soluble calcium competes with iron for complexation by citrate. This competition further lowers the effect of citrate on iron solubility in the presence of calcium. This example illustrates the importance of specificity for iron complexation relative to calcium and other ions for mobilization of iron by organic ligands in calcareous soils.

While absolute values of stability constants vary strongly depending on the nature of the organic ligand, the sequence of increasing stability of complexes with various metals is generally independent of the ligand. This is expressed in the empirical Irving–Williams sequence of complex stabilities involving divalent transition metals in the order $Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < Cu^{2+} > Zn^{2+}$ (Irving and Williams, 1953). Also, a linear relationship has been established between the log of the first hydrolysis constant of metal ions (of various oxidation states) and the log of the complex formation constants with ligands containing negative oxygen donor groups (Evers *et al.*, 1989). Therefore, ligands containing negative oxygen donor groups

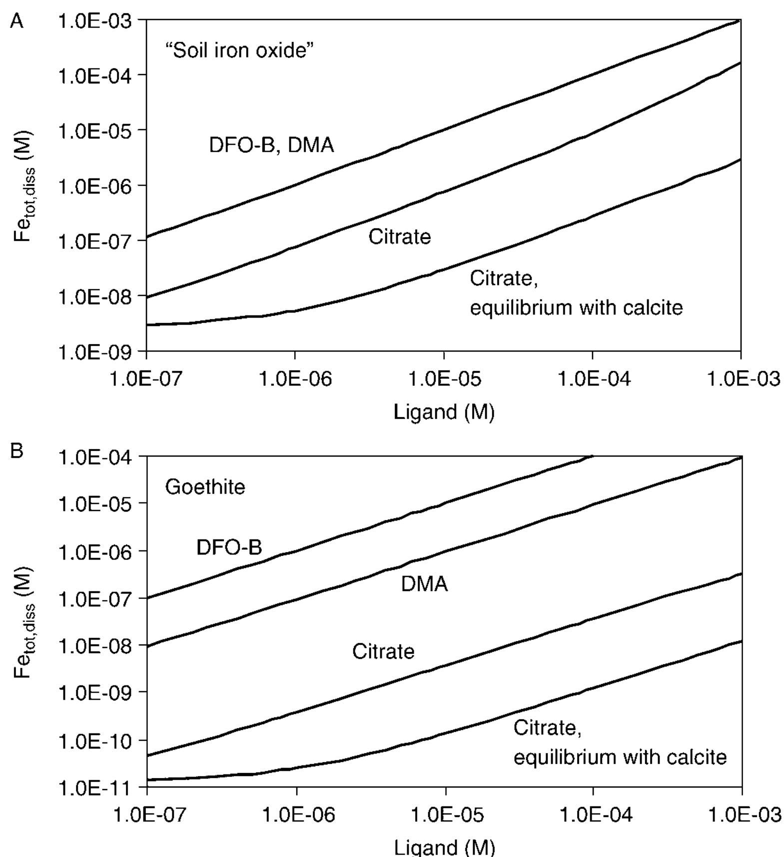


Figure 4 Equilibrium solubility of iron in the presence of: (A) "soil iron oxide" (Lindsay and Schwab, 1982) and (B) goethite as a function of soluble citrate, DMA, or DFO-B concentrations. Solubility of iron in the presence of DFO-B and DMA is not significantly influenced by the presence or absence of calcium. Iron solubility in the presence of citrate decreases in equilibrium with calcite at elevated rhizosphere CO_2 partial pressure (Gollany *et al.*, 1993) (pH = 6.8, $P_{CO_2} = 10^{-1.2}$ atm, $I = 0.1$ M). Under the conditions shown earlier, calcium citrate solid phases are undersaturated (De Robertis *et al.*, 1995). Equilibrium constants and solubility products are listed in Tables IV and V.

will typically form metal complexes with increasing stability constants in the order $Ca^{2+} < Zn^{2+} < Cu^{2+} < Al^{3+} < Fe^{3+}$. Citrate and DFO-B both follow this empirical relationship but the differences in formation constants are much larger for DFO-B complexes compared to citrate complexes. For example, the 1:1 formation constants of Ca^{2+} and Fe^{3+} complexes are $10^{2.64}$ and $10^{30.7}$ for DFO-B vs $10^{3.5}$ and $10^{11.2}$ for citrate ($I = 0.1$ M) (Martell *et al.*, 2001). The presence of neutral nitrogen donor groups (e.g.,

in mugineic acids) and steric factors, such as preorganization effects, can further increase the selectivity of the ligand for Fe^{3+} vs Ca^{2+} (Evers *et al.*, 1989; Hou *et al.*, 1998; Martell *et al.*, 1994; Spasojevic *et al.*, 1999).

C. Iron Complexes with Low-Molecular Weight Organic Acids

Low-molecular weight organic acids are commonly found in soils (Strobel, 2001). They are exuded by plant roots, bacteria, and fungi, and organic acid concentrations tend to be higher in the rhizosphere compared to bulk soil (Jones, 1998). It has been proposed that organic acids play a role in iron acquisition by strategy I plants (Jones *et al.*, 1996). For example, cluster roots exude organic acids with extremely high exudation rates in a localized area and in a short "exudative burst" that lasts for a couple of days or less (Hagstrom *et al.*, 2001). Organic acids released by cluster roots are mainly citrate and malate, which can reach millimolar concentrations in the rhizosphere soil solution (Gerke *et al.*, 1994; Neumann and Martinoia, 2002), triggering the precipitation of Ca–citrate in calcareous soil (Dinkelaker *et al.*, 1989). Strategy II plants increase exudation rates of organic acids under moderate iron limitation, while phytosiderophore exudation dominates at extreme iron limitation (Fan *et al.*, 1997, 2001).

Organic acids can increase both the solubility and dissolution rates of iron oxides (Zinder *et al.*, 1986). The solubility of "soil iron oxide" is between 0.1 and 0.2 mM at millimolar citrate concentrations in the absence of calcium. The iron solubility is almost two orders of magnitude lower in equilibrium with calcite due to the competing formation of calcium–citrate complexes as discussed earlier. However, the concentration of iron–citrate complexes is still in the micromolar range at millimolar citrate concentrations under these conditions, potentially providing a sufficient iron source for strategy I and II iron acquisitions. Reviews on various aspects of organic acids in soils are available (Abadía *et al.*, 2002; Dakora and Phillips, 2002; Jones, 1998; Jones *et al.*, 2003; Strobel, 2001).

D. Microbial Siderophore Complexes

Microbial siderophores have been considered as iron source for plant nutrition. Microbial siderophores are structurally diverse. Molecular masses range from 0.5 to 1.5 kDa (Matzanke *et al.*, 1989). Common ligating functional groups include α-hydroxycarboxylate, carboxylate, catecholate, and hydroxamate groups. Most siderophores are hexadentate and form 1:1 iron complexes. Tetradentate siderophores, such as rhodotorulic acid, form 1:2 or 2:3 complexes. Microbial siderophores have very high affinities for iron, and iron complexes dominate their speciation in equilibrium with iron

oxides over the whole pH range commonly found in soils. Known 1:1 stability constants of Fe(III)–siderophore complexes range from 10^{23} to 10^{52} compared to $10^{13.2}$ (Fe–citrate), $10^{27.7}$ (Fe–EDTA), and $10^{21.7}$ (Fe–HEDTA) (Martell *et al.*, 2001). Also, most siderophores have a high specificity for iron so that they bind iron in the presence of high concentrations of other cations. For example, Ca^{2+} cannot compete with protonation of hydroxamate groups of the microbial siderophore DFO-B (Fig. 5) even at high Ca^{2+} concentrations in carbonate-containing soils. Powell *et al.* (1980) estimated microbial siderophore concentrations in soil solutions of 10^{-7} to 10^{-8} M. Microbial siderophore concentrations are higher in the rhizosphere compared to bulk soil (Reid *et al.*, 1984b).

Due to their high affinity and specificity for iron, the presence of microbial siderophores has a strong effect on the solubility and transport of iron oxides. Therefore, a number of studies have focused on Fe complexes with microbial siderophores as iron sources for plant nutrition. Various strategy I plants were able to take up microbial siderophore complexes (Cline *et al.*, 1984; Crowley *et al.*, 1987, 1991; Johnson *et al.*, 2002). Iron uptake from iron complexes of hexadentate microbial siderophores by strategy II plants has been demonstrated (Crowley *et al.*, 1988; Reid *et al.*, 1984a), but various studies have concluded that it is rather inefficient (Bar-Ness *et al.*, 1991; Crowley *et al.*, 1992; Hördt *et al.*, 2000; Römheld and Marschner, 1986, 1990). The reasons for the low availability of microbial siderophore complexes to strategy II plants may include their high thermodynamic and kinetic stability that can inhibit ligand-exchange reactions with mugineic acids as discussed later.

An unusual microbial siderophore with regard to its structure and relatively low affinity and specificity for iron (compared to other microbial siderophores) is rhizoferrin (Fig. 5). Rhizoferrin is a fungal tetradentate hydroxyl-carboxylate siderophore. Its iron complexes are available to strategy I and II plants (Shenker *et al.*, 1995; Yehuda *et al.*, 1996). Equilibrium speciation calculations based on published stability constants of Ca–rhizoferrin complexes suggest that competition between Ca and Fe will inhibit the formation of significant concentrations of iron–siderophore complexes in calcareous soils. However, it was shown that rhizoferrin efficiently promotes dissolution of ferrihydrite at pH 8.7 with net dissolution rates comparable to mugineic acid (Shenker *et al.*, 1996, 1999) to concentration levels which seem to indicate that the stability of iron complexes has been underestimated relative to the stability of Ca complexes.

Microbial siderophore complexes undergo biological and chemical degradation reactions in soils and aqueous systems (Pierwola *et al.*, 2004; Warren and Neilands, 1964, 1965; Winkelmann *et al.*, 1999). The degradation products usually have a lower denticity and affinity for iron and an increased bioavailability to plant species. For example, iron complexes of hydrolysis products of coprogen have a higher reduction potential, and a

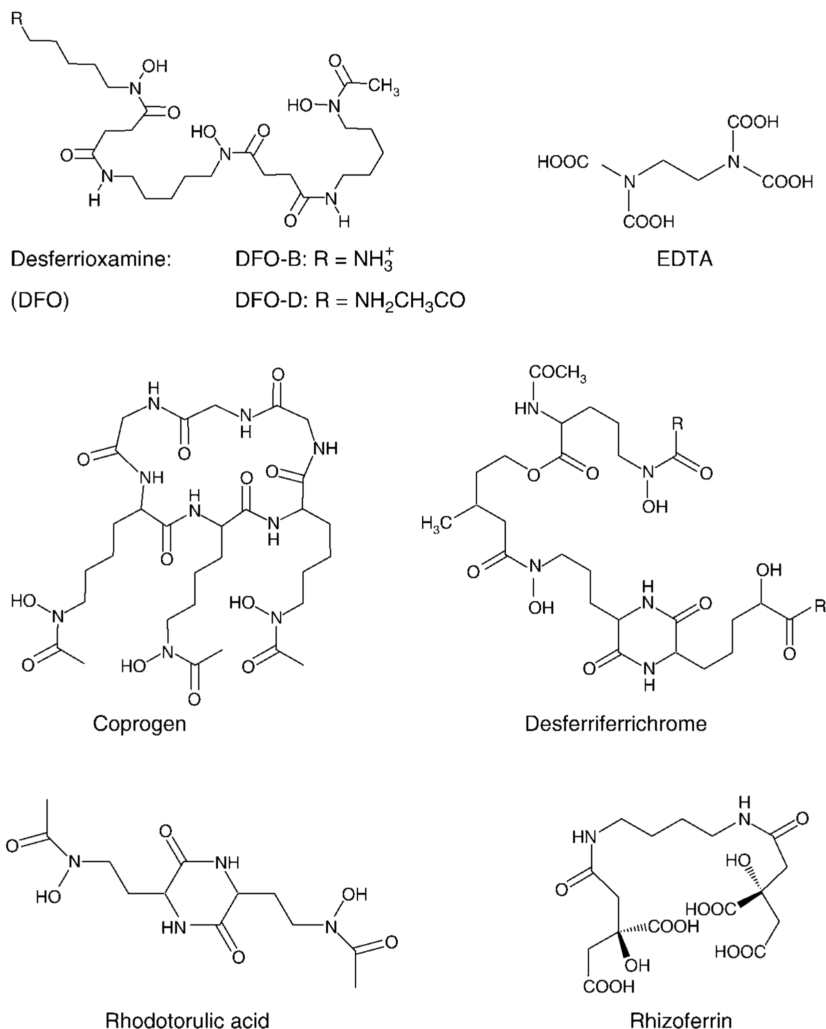


Figure 5 Selection of fungal and bacterial siderophores and the synthetic aminocarboxylate ligand EDTA. Rhizoferrin is a carboxylate siderophore, exuded by the fungus *Rhizopus* and related mucorales (Drechsel *et al.*, 1991). DFO-B, DFO-D, coprogen, and desferriferrichrome are trihydroxamate siderophores, rhodotorulic acid is a dihydroxamate siderophore.

lower thermodynamic and kinetic stability, compared to the parent compound, resulting in improved uptake by strategy I and II plants (Hördt *et al.*, 2000). Similarly, the photolysis of iron–siderophore complexes possessing α-hydroxycarboxylate groups leads to the reduction of Fe(III) and the

formation of lower affinity iron complexes, increasing the bioavailability of dissolved iron to phytoplankton (Barbeau *et al.*, 2001; Borer *et al.*, 2005). In light of these observations, it seems likely the plant availability of microbial siderophores in long-term uptake experiments and in the field may be related to their microbial or chemical degradation rates.

E. Natural Organic Matter

Natural organic matter in soils including humic acids and fulvic acids is usually associated with iron. Low-molecular weight organic acids and siderophores that have been discussed earlier are usually considered part of the NOM pool. Therefore, the role of NOM in plant iron nutrition that has been observed may be in part due to low-molecular weight organic acids as discussed earlier. A number of studies have demonstrated that this iron bound to NOM (or fractions of it) can serve as source for strategy I and strategy II plant iron acquisitions. It is difficult to draw generalizations on the plant availability of iron bound to NOM from different sources due to the contrasting properties regarding transport (immobile, soluble, or colloidal), and thermodynamics and kinetics of iron binding and release. However, in field and pot experiments it has been demonstrated that fulvic acid, humic acid, and water- and pyrophosphate-extractable fractions of humic substances as well as preparations of peat, manure, compost, coal, lignite, and sewage sludge improve iron uptake by strategy I and/or strategy II plants (Barak and Chen, 1982; Cesco *et al.*, 2002; Chen, 1996; Chen and Aviad, 1990; Chen *et al.*, 1999; Garcia-Mina *et al.*, 2004; Linehan and Shepherd, 1979; Pinton *et al.*, 1999). Besides its function as iron source, NOM has a range of effects on the physical, chemical, and biological properties of the soil and influences the physiology of plant roots. All of these factors can directly or indirectly influence plant iron acquisition.

EXAFS studies of iron binding by NOM at natural abundance levels and after addition of $FeCl_3$ demonstrated that organic complexation inhibits iron polymerization even in the neutral pH range (Rose *et al.*, 1998; Vilge-Ritter *et al.*, 1999). Important ligating groups for iron in humic substances are carboxyl (–COOH), carbonyl (=CO), phenolic hydroxyl (–OH), amine ($–NH_2$), imine (=NH), and sulfhydryl (–SH) (Blume *et al.*, 2002). Adjacent organic ligating groups can chelate iron in five- or six-membered rings. Electron spin resonance studies of Fe–fulvic acid complexes showed complexation by carboxylic and phenolic OH groups (Senesi, 1990). A fraction of the iron content of purified humic substances can be bound to minerals that are tightly associated with the organic matter (Davies *et al.*, 1997). Due to the range of possible binding configuration within humic substances, iron reacts with sites of varying thermodynamic and kinetic stability (Burba, 1994; Tipping *et al.*, 2002).

The solubility of iron in equilibrium with iron oxides is strongly influenced by the presence of dissolved organic matter (DOM). Tipping *et al.* (2002) modeled equilibrium speciation of iron in the presence of ferrihydrite and 10 mg liter^{-1} fulvic acid (representing freshwater DOM) at 3-mM Ca concentrations. In the pH range between 6.5 and 7.5, they predicted iron solubilities in the micromolar range. The addition of up to 7 mg liter^{-1} humic acid to 0.7 N NaCl solutions at pH 8 increased the solubility of iron in equilibrium with freshly precipitated ferrihydrite to 10^{-8} to 10^{-7} M (Liu and Millero, 1999). Cesco *et al.* (2000) demonstrated that water-extractable humic substances increased the dissolution rate and solubility of freshly precipitated ferrihydrite. Also, it served to extract iron from various soil types including carbonatic soils in column experiments.

Soil solutions contain several ten to several hundred mg liter^{-1} DOM, including organic acids and higher molecular weight fractions (Zsolnay, 1996). Therefore, significant concentrations of Fe could be associated with DOM in soils. DOM as the mobile fraction of soil organic matter is of particular interest for plant nutrition as it can act as an iron shuttle for strategy I and II plants. However, phytosiderophores themselves can act as iron shuttles and also scavenge iron from the immobile soil organic matter fractions.

V. THE CHEMISTRY OF PHYTOSIDEROPHORES IN THE RHIZOSPHERE

The exudation of phytosiderophores has a strong effect on the geochemistry of iron in the rhizosphere. In calcareous soils, phytosiderophore complexes become the dominant soluble iron species. This increases the bioavailability of iron for graminaceous plants that take up the phytosiderophore complexes and for rhizosphere microorganisms that can scavenge iron from the complexes. Phytosiderophores increase the solubility of iron-bearing minerals and accelerate their dissolution. Also, phytosiderophores can serve as iron shuttles so that immobile iron pools (solid, adsorbed, or complexed by organic matter) that are not in direct contact with the plant root can be scavenged.

A. Structure of Phytosiderophores

Mugineic acid and its derivatives (commonly called mugineic acids or MAs) are hexadentate ligands with aminocarboxylate and hydroxycarboxylate functional groups (Fig. 6). The ligands are synthesized by hydroxylation of the parent compound nicotianamine (Ma and Nomoto, 1993; Mori and

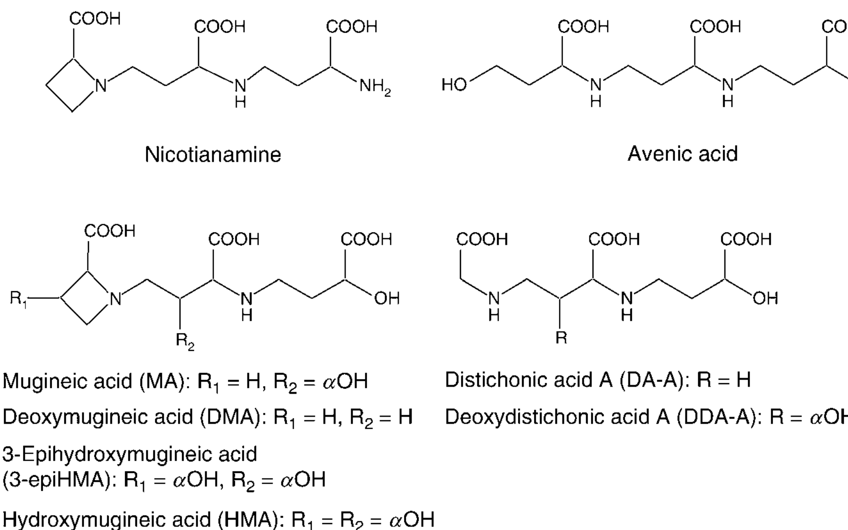


Figure 6 Structure of mugineic acid derivatives and nicotianamine.

Nishizawa, 1987). Their molecular weight ranges from 278 (DDA-A) to 336 (HMA, epi-HMA).

B. Concentrations of Phytosiderophores in the Rhizosphere

In hydroponic culture studies, overall phytosiderophore release rates are a function of the nutritional status of the plant. The nutritional status is not only a function of the free iron activity in solution but also of plant age (Gries *et al.*, 1995). The observed release rates of phytosiderophore under strong iron deficiency greatly exceed iron-uptake rates required for normal growth. Phytosiderophore exudation by plant roots is highly restricted in time and space. Diurnal exudation for only a few hours during the light period is commonly observed (Marschner *et al.*, 1986a; Takagi *et al.*, 1984). Exceptional continuous exudation by *Z. mays* L. cv. Alice has been observed (Yehuda *et al.*, 1996). The release of siderophores varies along the root and is most pronounced in apical root zones (Marschner *et al.*, 1987). These restrictions along with known exudation rates and estimated microbial degradation rates have been used as parameters of a radial diffusion model to estimate the local distribution of phytosiderophores in the rhizosphere (Römheld, 1991). The model predicts a strong gradient of phytosiderophore concentrations away from the root surface with average concentrations of 1 mM within the first 0.25 mM during the period of maximum exudation rates.

Shi *et al.* (1988) extracted phytosiderophore from the rhizosphere of iron-stressed barley after several days of growth in calcareous soil. They found average concentrations in the low micromolar range. Considering that the sampling was not restricted to the apical root zones and the time of maximum exudation and understanding that plant iron limitation was somewhat relaxed by the actual success of the iron acquisition strategy (which is likely to lead to decreasing phytosiderophore exudation rates), these results are not inconsistent with the predictions by Römheld (1991).

C. Speciation of Phytosiderophores and Iron in Solution

Over a wide pH range, mugineic acids are zwitterionic in aqueous solution. The carboxylate groups of MA, DMA, and epi-HMA have pK_a values between 2.3 and 3.4. Their secondary and tertiary amino groups have pK_a values between 7.1 and 10.0 (all pK_a measured at $I = 0.1$ M) (Table II). The terminal hydroxy group deprotonates only on coordination of metal ions such as iron and cobalt (Mino *et al.*, 1983; Murakami *et al.*, 1989). A pK_a of approximately 17.1 for the terminal hydroxy group of MA derivatives was estimated by Murakami *et al.* (1989). The hydroxylation of the backbone of the MAs has an effect on the pK_a of the amine groups that become increasingly acidic due to the electron-withdrawing effect of the OH groups (Murakami *et al.*, 1989) and intramolecular hydrogen bonding between adjacent hydroxyl and amine groups (von Wirén *et al.*, 2000).

Table II
Published pK_a and Fe Complex Formation Constants of Mugineic Acids and Nicotianamine

L	pK_{a1}	pK_{a2}	pK_{a3}	pK_{a4}	pK_{a5}	pK_{a6}	log β_{110}[a]	log β_{11-1}[b]	log $K_{Fe(II)-L-}$
DMA[c]	2.35[d,e]	2.74[d,e]	3.19	8.25	10.00	17.1[e]	18.38	16.25	10.45
MA[c]	–	–	3.23	7.94	9.85	17.1[e]	17.71	15.39	10.14
MA[d]	2.39	2.76	3.40	7.78	9.55	–	17.7	–	–
MA[f]	2.39	2.76	3.40	7.78	9.55	–	18.1	–	8.1
Epi-HMA[c]	2.35[d,e]	2.74[d,e]	3.23	7.10	9.62	17.1[e]	–	15.49	10.02
NA[g]	–	–	2.2	7.01	9.14	10.17	–	–	12.8
NA[h]	–	–	2.86	6.92	9.14	10.09	20.6	–	–

[a]$\beta_{110} = [FeL]/([Fe^{3+}]\,[L^{3-}])$.
[b]$\beta_{11-1} = [FeOHL^{-1}]\,[H^+]/([Fe^{3+}]\,[L^{3-}])$.
[c]Murakami *et al.* (1989), $I = 0.1$ M KNO_3.
[d]von Wirén *et al.* (2000), $I = 0.1$ M KCl.
[e]Estimated.
[f]Sugiura *et al.* (1981), $I = 0.1$ KCl.
[g]Anderegg and Ripperger (1989), $I = 0.1$ KNO_3.
[h]von Wirén *et al.* (1999), $I = 0.1$ M KCl.

Siderophores of the MA family coordinate ferric iron in a distorted octahedral coordination by three five-membered rings: (1) via the carboxylate groups adjacent to the azetidine ring and the azetidine nitrogen, (2) via the central carboxylate group and the secondary amine nitrogen, and (3) via the terminal carboxylate group and the terminal hydroxy group (Mino *et al.*, 1983; Murakami *et al.*, 1989; Sugiura *et al.*, 1981). Iron binding involves the deprotonation of the carboxylate, terminal hydroxyl, and amine groups, resulting in a pH-dependent net negative charge of the complex over most of the soil typical pH range (von Wirén *et al.*, 2000). At low pH, a protonated complex is found with no net charge (Murakami *et al.*, 1989). Based on electrophoretic measurements, von Wirén *et al.* (2000) suggested that protonation of the azetidine nitrogen at pH < 7 and subsequent exchange of the carboxylate ligating group leads to the formation of a tetradentate complex that has no charge. They concluded that the neutral tetravalent Fe–DMA complex becomes important below pH 7. This is in contradiction to the data of Murakami *et al.* (1989) who concluded that the neutral species of all siderophores becomes important only below pH 4 and becomes dominant at very acidic pH. von Wirén *et al.* (2000) reported a stability constant of an iron–MA complex at pH 7.4 but no protonation constant of the complex. Also, the stability constants of the MA and DMA iron complex given by von Wirén *et al.* (1999, 2000) underpredict by several orders of magnitude the dissolved iron concentrations in the presence of various iron oxides at pH 7 and 8 that have been observed in studies of iron oxide dissolution in the presence of DMA and MA (Hiradate and Inoue, 1998a,b, 2000; Reichard *et al.*, 2005). Therefore, pK_a and complex formation constants given by Murakami *et al.* (1989) are used for equilibrium speciation calculations in this publication. NA does not possess the terminal hydroxyl group and, therefore, does not form negatively charged complexes (von Wirén *et al.*, 2000). A summary of published protonation and complex formation constants is given in Table II. The constants used for equilibrium speciation calculations for this publication (corrected for $I = 0$) are listed in Tables IV and V.

The reduction potentials $E_{1/2}$ vs NHE of iron–phytosiderophore complexes are -102 mV [Fe(III)MA] and 181 mV [Fe(III)NA] at pH 7 (Mino *et al.*, 1983). Reichman and Parker (2002) calculated redox potentials based on a set of published stability constants (corrected to $I = 0.1$ M) of 53 and 278 mV for the DMA and NA iron complexes, respectively. These redox potentials are higher than those of most hexadentate microbial siderophores (Boukhalfa and Crumbliss, 2002) allowing the enzymatic reduction of phytosiderophore complexes by NAD(P)H, as has been verified experimentally (Mino *et al.*, 1983).

Like other aminocarboxylates, mugineic acids coordinate not only iron but a range of other divalent and trivalent metal ions. The stability of the

metal complexes increases with increasing basicity of the ligand. For example, mugineic acid forms stable hexadentate Cu(II) complexes in distorted octahedral geometry (Murakami *et al.*, 1989). The effect of competing metal ions on strategy II iron acquisition is discussed in the next section.

D. Effect of Phytosiderophores on Iron Solubility

It has been mentioned earlier that siderophore concentrations in the rhizosphere may reach several hundred micromolar or even millimolar concentrations. Figure 7 shows calculated equilibrium concentrations of iron in the presence of important soil minerals and at a phytosiderophore concentration of 500 μM as a function of pH. In the presence of "soil iron oxide" and in the pH range between 4 and 8, iron solubility is between 400 and 500 μM, and iron complexes constitute the dominant siderophore species (>80%). Even in the presence of goethite, a crystalline iron oxide, the iron solubility is in the range of 10–200 μM.

Several studies of iron oxide dissolution from undersaturation in the presence of MA, epi-HMA, and DMA have been published (Chang *et al.*, 1999; Hiradate and Inoue, 1998a,b, 2000; Reichard *et al.*, 2005; Zhang *et al.*, 1991b). These studies give a lower limit on iron solubility in the presence of phytosiderophores and crystalline and noncrystalline iron oxides, which is consistent with equilibrium solubility predictions using the set of stability and solubility constants chosen here.

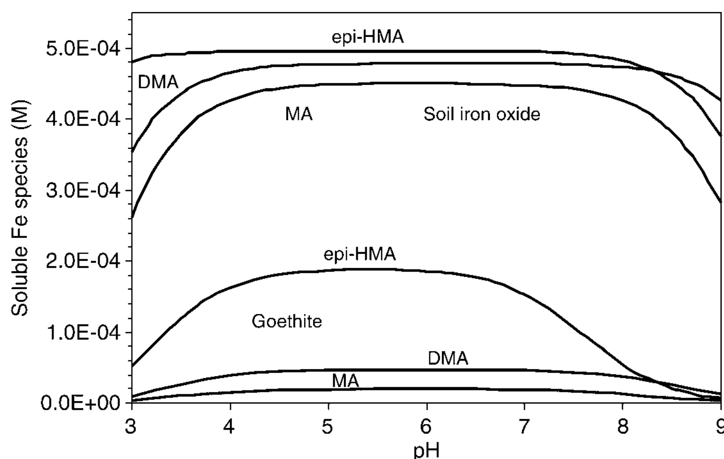


Figure 7 Equilibrium solubility of iron in the presence of goethite or "soil iron oxide" (Lindsay and Schwab, 1982) and 500 μM epi-HMA, DMA, or MA, respectively, as a function of pH. Equilibrium constants and solubility products are listed in Tables IV and V.

Comparing these predictions with required iron–phytosiderophore concentrations for normal growth of graminaceous plants in hydroponic culture as estimated by Zhang *et al.* (1991b) (500 μM near the rhizoplane during times of maximum exudation), it can immediately be inferred that even the comparatively low solubility of crystalline iron oxide phases does not limit iron acquisition of strategy II plants. Even at phytosiderophore rhizosphere concentrations in the low μM range that have been observed by Shi *et al.* (1988), the solubility of goethite would be above 10^{-8} to 10^{-7} M (Kraemer, 2004), a level that has been suggested as critical level for plant nutrition (Lindsay and Schwab, 1982). This is consistent with observations of normal growth of graminaceous plants with ferrihydrite or goethite as the sole iron source (Bertrand and Hinsinger, 2000; Reichard *et al.*, 2005; Zhang *et al.*, 1999).

Prediction of strong competition of divalent metal ions over iron for complexation by phytosiderophores has led to the hypothesis that iron dissolution should be effectively inhibited by the formation of Cu and Zn complexes in soils (Crowley *et al.*, 1987). Competitive effects of Cu and Zn on ferrihydrite solubility were observed (Zhang *et al.*, 1991b). In Cu-contaminated soil, iron deficiency leads to increased Cu uptake by wheat, presumably due to mobilization by phytosiderophores (Chaignon *et al.*, 2002). However, the reaction of MA with uncontaminated calcareous soils leads to strong mobilization of iron and only moderate mobilization of Cu (Singh *et al.*, 1992). Additions of Cu and Zn salts to a calcareous soil had only small effects on iron mobilization by epi-HMA (Zhang *et al.*, 1991b). Unlike iron, soluble Cu concentrations in unpolluted soils are not controlled by solubility equilibria, but by adsorption on mineral surfaces and by complexation by organic ligands including humic substance. Therefore, it is prerequisite to consider the competition of other ligands for binding of Cu in order to predict the effect of Cu on iron speciation and solubility in the presence of phytosiderophores.

Phytosiderophores have only a low affinity for calcium. This is a prerequisite for mobilization of iron in calcareous soils. In agreement with observations (Zhang *et al.*, 1991b), the calculated solubility of ferrihydrite in the presence of 0.5 μM DMA is approximately the same in the presence or absence of calcite [rhizosphere $P_{CO_2} = 9$ kPa (Gollany *et al.*, 1993); pH = 6.8, stability constants as listed in Tables IV and V].

E. Adsorption of Phytosiderophores on Iron Oxides

Adsorption of siderophores on mineral surfaces can have various effects on plant iron acquisition. It leads to loss of the siderophore (and/or the siderophore–iron complex) from solution. This loss potentially decreases the equilibrium concentration of iron in solution. On the other hand, adsorption

of siderophores is the first and necessary step of a ligand-controlled dissolution mechanism that can increase the rates of iron dissolution from minerals.

DMA adsorption on goethite can be described by a Langmuir-type isotherm:

$$[\mathrm{DMA}]_{\mathrm{ads}} = \frac{n_{\max} K_{\mathrm{ads}} [\mathrm{DMA}]_{\mathrm{diss}}}{1 + K_{\mathrm{ads}} [\mathrm{DMA}]_{\mathrm{diss}}} \tag{10}$$

where $n_{\max}$ (μmole m^{-2}) is the maximum DMA surface concentration, and K_{ads} is an affinity parameter. Reichard *et al.* (2005) reported maximum DMA surface concentrations $n_{\max}$ of 0.58 and 0.5 μmole m^{-2} with corresponding affinity parameters of 0.02 and 0.01 at pH 6 and 8, respectively. This is consistent with reported surface densities of mugineic acid on goethite, hematite, and lepidocrocite in the range of 0.3–0.36 μmole m^{-2} at dissolved MA concentrations of less than 250 μM (Inoue *et al.*, 1993). Higher sorption densities of >0.45 μmole m^{-2} have been observed on ferrihydrite surfaces (Inoue *et al.*, 1993). Significant adsorption competition of sulfate and phosphate (at concentrations of 0.1 M, respectively) with MA (100 μM) has been observed (Hiradate and Inoue, 1998b). Reichard *et al.* (2005) investigated the effect of pH on adsorption of DMA at constant total DMA concentrations. They found a monotonous decrease of surface concentrations between pH 5 (0.7 μmole m^{-2}) and pH 9 (0.05 μmole m^{-2}). This behavior is typical for ligands possessing negative charge.

Adsorption of Fe–MA complexes has been studied by addition of 100 μM 1:1 Fe–MA complexes to iron oxide suspensions (Inoue *et al.*, 1993). Comparing the results with model calculations of the solubility of iron in the presence of 100 μM MA concentrations and crystalline iron oxides, it appears that iron was strongly oversaturated in these experiments (with the possible exception of ferrihydrite), and precipitation of iron was likely a major driver in the removal of iron from solution. However, note that the loss of iron from solution decreased as the isoelectric point of the oxide was approached. At alkaline pH, no loss of iron by either adsorption or precipitation was observed. Reichard *et al.* (2005) observed adsorption of Fe–DMA complexes on goethite between pH 5 and 9 without oversaturating the solution by maintaining an excess of DMA (500 μM) over Fe (10 μM). Generally, adsorbed concentrations were much lower than observed by Inoue *et al.* (1993), presumably due to the lack of surface precipitation. Adsorption of the Fe–DMA complex decreased with increasing pH as observed previously but significant adsorption was observed even at pH 9. These observations are consistent with a study on Fe–EDTA adsorption on iron and aluminum oxides, where ternary surface complexation with ligand bridging in the acidic pH range and metal bridging in the neutral to alkaline range was observed (Nowack *et al.*, 1996).

VI. GEOCHEMICAL ASPECTS OF IRON SHUTTLING

Soluble iron complexes can serve as efficient iron shuttles for plant nutrition if the following conditions are met:

1. The ligand concentration, affinity, and specificity for iron must be sufficiently high to maintain significant soluble iron concentrations against the low solubility of iron oxide phases in a solution that contains competing ions at high concentrations (e.g., calcium).
2. The concentration of the iron complex must be large enough to satisfy plant iron demand or the rate of iron acquisition by the ligand from other pools (e.g., iron oxide dissolution, ligand exchange from particulate or sorbed Fe–humic complexes) must be at least in the same order as the iron uptake rate by the plant.
3. The complexes must have a sufficiently high redox potential for enzymatic reduction (strategy I plants) or a sufficiently low thermodynamic stability to undergo ligand-exchange reactions with phytosiderophores (strategy II plants).
4. The complexes must have a sufficiently high kinetic lability to undergo ligand-exchange reactions within the timescales given by the diurnal phytosiderophore exudation window.

As this discussion illustrates, thermodynamic and kinetic considerations are equally important in the understanding of strategy II iron acquisition. One prerequisite for iron shuttling, the thermodynamic stability and specificity of soluble iron complexes has been already discussed earlier. In this section, we will discuss some important chemical mechanisms involved in iron shuttling (see Fig. 2), namely iron oxide dissolution and ligand-exchange reactions.

A. Effect of Organic Ligands on Iron Oxide Dissolution Rates

Ligands facilitate the dissolution of iron oxides in two ways: by attacking the mineral surface in a ligand-controlled dissolution mechanism and by decreasing the solution saturation state (a prerequisite for any dissolution mechanism to be set in motion). A rate law for steady state ligand-controlled dissolution is (Furrer and Stumm, 1986; Kraemer and Hering, 1997):

$$R_{\text{net}} = \Sigma k_{\text{Ln}}[\text{L}_n]_{\text{ads}} f(\Delta G) \qquad (11)$$

where R_{net} is the net dissolution rate (mole/h m^{-2}), $[\text{L}_n]_{\text{ads}}$ are the surface concentrations of all ligands adsorbed to the oxide surface promoting mineral dissolution (mole m^{-2}), k_{Ln} are the rate coefficients of ligand-controlled

dissolution in the presence of each ligand Ln, and $f(\Delta G)$ is a function of the solution saturation state (expressed as Gibbs free energy of the dissolution reaction). The $f(\Delta G)$ is 1 at strong undersaturation, decreases as equilibrium is approached, and becomes 0 at equilibrium (Kraemer and Hering, 1997). Therefore, at strong undersaturation Eq. (11) reduces to the more familiar rate law (Furrer and Stumm, 1986).

$$R_{\text{net}} = \Sigma k_{\text{Ln}}[\text{L}n]_{\text{ads}} \tag{12}$$

Based on Eq. (12), a linear correlation between adsorbed ligand concentrations and dissolution rates is diagnostic for a ligand-controlled dissolution mechanism. For example, goethite dissolution rates are linearly related to adsorbed DMA concentrations at pH 8, resulting in a Langmuir type relationship between soluble DMA concentrations and dissolution rates (Reichard *et al.*, 2005). Rate coefficients for steady state iron oxide dissolution in the presence of natural and synthetic organic ligands including microbial and plant siderophores have been published.

As seen in Table III, the steady state rate coefficients for goethite dissolution in the presence of the phytosiderophore DMA have the same order of magnitude as those of oxalate and EDTA and tend to increase with increasing pH. A common explanation for the influence of pH on dissolution rate coefficients are changes in the surface speciation of the ligand (Nowack and Sigg, 1997) or deprotonation of adjacent ligating groups at the mineral surface (Kraemer *et al.*, 1998). The effect of increasing rate coefficients is compensated by decreasing adsorbed DMA concentrations with increasing pH as discussed earlier, resulting in maximum dissolution rates at pH 6. Observed net dissolution rates are lower than those predicted by Eq. (12) due to readsorption of Fe–DMA complexes, particularly at pH < 7 as discussed earlier (Reichard *et al.*, 2005). In several studies, dissolution of iron oxides in the presence of MA over a fixed period of time has been observed.

Table III

Rate Coefficients of Ligand-Promoted Dissolution of Goethite in the Presence of Various Siderophore and Nonsiderophore Ligands

Ligand	pH	k_L [h^{-1}]	References
DFO-B	6.5	0.05	Cocozza *et al.*, 2002; Kraemer *et al.*, 1999
DFO-D_1	6.5	0.06	Cocozza *et al.*, 2002; Kraemer *et al.*, 1999
Oxalate	6	0.001	Reichard *et al.*, submitted
EDTA	5.3	0.0016	Nowack and Sigg, 1997
DMA	5	0.0008	Reichard *et al.*, 2005
DMA	6	0.003	Reichard *et al.*, 2005
DMA	7	0.003	Reichard *et al.*, 2005
DMA	8	0.004	Reichard *et al.*, 2005

Inoue *et al.* (1993) chose reaction times so that ferrihydrite reached solubility equilibrium (4 h). Other iron oxide phases may or may not have reached equilibrium in the same time. Therefore, reported dissolved concentrations (after 4 h) may be controlled by equilibrium thermodynamics, others by dissolution kinetics and cannot easily be compared. However, observed soluble iron concentrations after 4 h reaction time in the presence of MA decreased in the order ferrihydrite $>>$ lepidocrocite $\geq$ goethite $=$ hematite.

Observed goethite dissolution rate coefficients in the presence of microbial siderophores (DFO-B and DFO-B) are higher than those of DMA-promoted dissolution. However, observed surface concentrations of the microbial siderophores are low, even at high soluble concentrations above 100 μM resulting in net goethite dissolution rates in the same range as DMA-promoted dissolution (Cheah *et al.*, 2003; Cocozza *et al.*, 2002; Kraemer *et al.*, 1999). For a detailed discussion of ligand-controlled dissolution in the presence of microbial siderophores, see Kraemer (2004).

1. Inhibitory Effects of Inorganic Ligands and Humic Substances on Ligand-Controlled Iron Oxide Dissolution

The model of ligand-controlled dissolution presented here assumes that parallel dissolution mechanisms are independent in the sense that a rate coefficient k_{Ln} for ligand-controlled dissolution in the presence of the corresponding ligand L_n is independent of the presence of other adsorbed or soluble ligands. However, the adsorbed ligand concentrations $(\mathrm{L}_n)_{\mathrm{ads}}$ are clearly not independent of other ligands competing for adsorption. For example, phosphate has a high affinity for adsorption at iron oxide surfaces, but it does not promote iron oxide dissolution. Due to its high affinity for adsorption, it can competitively displace other ligands (that promote iron oxide dissolution) in a ligand-exchange reaction. Therefore, phosphate can have an inhibitory effect on ligand-controlled dissolution (Bondietti *et al.*, 1993; Jones *et al.*, 1996). Strong inhibition of goethite and hematite dissolution in the presence of MA was observed at high concentration (0.1 M) of phosphate and sulfate (Hiradate and Inoue, 1998a,b). Under the same conditions, lepidocrocite and ferrihydrite dissolution was partially inhibited by phosphate, while sulfate inhibited the readsorption of Fe–MA complexes, which led to an increase of soluble Fe–MA concentrations below pH 7 relative to similar experiments in the absence of sulfate (Hiradate and Inoue, 1998b). Silicate inhibited the dissolution of ferrihydrite above pH 8 and at silicate concentrations above 0.2 mM (Watanabe and Matsumoto, 1994).

Humic substances can have similar inhibitory effects on oxide dissolution. Ochs *et al.* (1993) found that humic substances increased dissolution rates of γ-Al_2O_3 at pH 3, but inhibited dissolution at higher pH. They attributed the

inhibitory effect to the formation of unreactive polynuclear surface complexes. Also, the concomitant decrease or even reversal (Tipping and Cooke, 1982) of the usually positive surface charge of iron oxides (in the acidic to slightly alkaline pH range) tends to decrease adsorption of negatively charged ligands.

2. Synergistic Effects of Organic Acids on Phytosiderophore-Controlled Iron Oxide Dissolution

An obvious prerequisite for dissolution is that the solution is undersaturated with respect to the dissolving mineral. In a nonequilibrium system, organic ligands can decrease the solution saturation state by iron complexation in solution. The effect of the solution saturation state (i.e., the Gibbs free energy change of the dissolution reaction ΔG) is quantitatively expressed in the rate law Eq. (11) as $f(\Delta G)$. At a given soluble iron concentration, the effect of a ligand on ΔG depends on the ligand concentration and on its affinity for iron. For example, Jones *et al.* (1996) estimated that citrate does not have a sufficient affinity for iron to increase the solubility of ferrihydrite in the rhizosphere at pH $\geq$ 7 to a level that supports plant growth. In contrast, microbial and plant siderophores have a strong effect on the solution saturation state even at small free concentrations due to their extremely high affinity for iron. Therefore, siderophores can indirectly facilitate dissolution by increasing the iron solubility without direct participation in mineral surface reactions (Cheah *et al.*, 2003; Reichard *et al.*, submitted, b). For example, Cheah *et al.* (2003) observed no dissolution of goethite due to its low solubility at pH 5 at oxalate concentrations $<$100 μM. However, oxalate did accelerate goethite dissolution in the presence of the microbial siderophore DFO-B. This resulted in a synergistic effect, where the presence of DFO-B facilitated a ligand (i.e., oxalate)-controlled dissolution mechanism. Similar synergistic effects have been observed in the presence of malonate, fumarate, and succinate in combination with DFO-B (Reichard *et al.*, submitted, b). It is intriguing to speculate that the coexudation of phytosiderophores and organic acids by iron-limited strategy II plants (Fan *et al.*, 1997, 2001) may be related to their synergistic effect on iron oxide dissolution.

Phytosiderophore are exuded diurnally for a few hours with maximum release rates 6 h after sunrise (Marschner, 1995). This strategy minimizes bacterial phytosiderophore degradation (Crowley and Gries, 1994), but it also reduces the time during which iron can be mobilized, impairing iron acquisition from crystalline iron oxide minerals that dissolve via slow surface-controlled dissolution mechanisms. However, the diurnal phytosiderophores release creates a strong nonsteady state with respect to the

solution saturation state and surface chemistry of iron-bearing mineral phases. These nonsteady state conditions trigger fast iron oxide dissolution reactions if other ligands, such as oxalate, citrate, or malate, are also present (Reichard *et al.*, 2005, submitted, b). Such organic ligands are common in the rhizosphere, as discussed earlier, and are coexuded by iron-limited grasses (Fan *et al.*, 1997). The rapid iron release in response to transient phytosiderophore exudation partly compensates for decreased iron release rates during the rest of the day thus satisfying nutritional demands (Reichard *et al.*, submitted, a). A mechanism of nonsteady state iron oxide dissolution was proposed, where a labilizing ligand (e.g., oxalate or malonate) adsorbs at the mineral surface by a ligand-exchange mechanism. The adsorbed ligands catalyze a surface reaction leading to the formation of kinetically labile iron surface centers in pseudoequilibrium with a low concentration of soluble iron complexes. On release of phytosiderophores, the labilized iron can be efficiently dissolved (Reichard *et al.*, submitted, b).

B. Thermodynamics and Kinetics of Ligand-Exchange Reactions with Phytosiderophores as Receiving Ligands

It has been observed that variations of the uptake rate of iron from organic iron complexes by strategy II plants follow the same diurnal pattern as release rates of phytosiderophores by the plant roots and that external supply of phytosiderophores to nutrient solutions increase the uptake rates (Cesco *et al.*, 2002; Yehuda *et al.*, 1996). From these observations, it has been concluded that iron acquisition from organic complexes by strategy II plants involves a ligand-exchange reaction that results in the release of iron from the organic ligands and the subsequent formation of iron–phytosiderophore complexes.

1. Ligand Exchange Equilibria

As discussed earlier, it has been established that strategy II plants acquire iron from organic complexes by ligand-exchange reactions with phytosiderophores as receiving ligands. Figure 8A shows equilibrium complexation of 1 μM Fe(III) by DMA in the presence of competing ligands as a function of total DMA concentrations. EDTA at micromolar concentrations can only compete with DMA in the absence of calcium. In the presence of calcium, EDTA inhibits precipitation of ferrihydrite (at low DMA concentrations) but DMA efficiently scavenges iron from EDTA. High concentrations of citrate (1 mM) compete only at DMA concentrations below 10 μM and in the absence of calcium. Micromolar concentrations of the microbial siderophore

DFO-B compete strongly with high concentrations of DMA for iron complexation independent of the presence or absence of calcium. The much higher affinity of DFO-B for iron compared to phytosiderophores was experimentally verified in a ligand-exchange experiment where 100 μM epi-HMA did not bind significant concentrations of iron in the presence of 200 μM Fe–DFO-B at pH 6 (Hördt *et al.*, 2000). This is consistent with equilibrium calculations using the set of equilibrium constants listed in Tables IV and V. At millimolar phytosiderophore concentrations that may be realized in the apoplast or very close to the root surface, ligand exchange may lead to the formation of low concentrations of iron–phytosiderophore complexes in a range that may partially satisfy iron requirements. However, slow ligand exchange rates may further reduce the efficiency of this reaction for iron acquisition as discussed later.

Due to large variations in the stability of Fe–siderophore complexes, it is difficult to draw generalizations on their availability for plant uptake. For example, DMA is able to efficiently sequester iron from the iron–rhodotorulic acid (Fe_2RA_3) complex (Fig. 8B). Rhodotorulic acid is a tetradentate siderophore forming binuclear complexes with somewhat lower stability compared to the other siderophore complexes shown here. Zhang *et al.* (1991a) found higher iron uptake via an apoplastic pathway in the presence of the rhodotorulic acid complex compared to the DFO-B complex. However, they did not report if rhodotorulic acid was present in (molar) excess over iron. Due to the stoichiometry of the dominant complex, the

Table IV
pK_a of Organic and Inorganic Ligands, Corrected to Zero Ionic Strength with the Davies Equation $T = 298.15$ K

L	pK_{a1}	pK_{a2}	pK_{a3}	pK_{a4}	pK_{a5}
DMA	2.13[a]	2.74[a]	3.4[b]	8.69[b]	10.66[b]
MA	2.17[c]	2.76[c]	3.45[b]	8.38[b]	10.51[b]
Epi-HMA	2.13[a]	2.74[a]	3.45[b]	7.54[b]	10.28[b]
DFO-B[d]	8.32	9.06	9.73	11.06	–
Ferrichrome[d]	8.33	9.44	10.49	–	–
Coprogen[d]	7.85	9.3	9.82	–	–
Rhodotorulic acid[d]	8.71	9.88	–	–	–
Citrate[d]	3.13	4.76	6.4	–	–
EDTA[d]	1.5	2.22	3.13	6.27	10.95
Carbonate[d]	6.35	10.33	–	–	–

[a]von Wirén *et al.* (2000).
[b]Murakami *et al.* (1989).
[c]Sugiura *et al.* (1981).
[d]Martell *et al.* (2001).

Table V
Thermodynamic Formation Constants, Corrected to Zero Ionic Strength with the Davies Equation $T = 298.15$ K

Reaction	log K	Reaction	log K
Complex formation constants		$Coprogen^{3-} + Fe^{+} = FeCoprogen$	32.18[a]
$Ca^{2+} + CO_3^{2-} = CaCO_3$	3.2[a]	$FeCoprogen + H^{+} = FeHCoprogen^{+}$	–0.5[a]
$Ca^{2+} + HCO_3^{-} = CaHCO_3$	1.27[a]	$RA^{2-} + Fe^{3+} = FeRA^{+}$	23.31[a,f]
$MA^{-4} + Fe^{3+} = FeMA^{-}$	19.69[c]	$3RA^{2-} + 2\ Fe^{3+} = Fe_2RA_3$	23.31[a,f]
$MA^{-3} + Fe^{3+} + H_2O =$	17.15[c]	Fe hydrolysis constants	
$Fe(OH)MA^{-} + H^{+}$		$Fe^{3+} + OH^{-} = FeOH^{2+}$	11.81[a]
$MA^{-3} + Ca^{2+} = CaMA^{-}$	5.13[c]	$Fe^{3+} + 2OH^{-} = Fe(OH)_2^{+}$	23.4[a]
$DMA^{-4} + Fe^{3+} = FeDMA^{-}$	20.36[c]	$Fe^{3+} + 4OH^{-} = Fe(OH)_4^{-}$	34.4[a]
$DMA^{-3} + Fe^{3+} + H_2O =$	18.01[c]	$2Fe^{3+} + 2OH^{-} = Fe_2(OH)_2^{4+}$	25.14[a]
$Fe(OH)DMA^{-} + H^{+}$		$3Fe^{3+} + 4OH^{-} = Fe_3(OH)_4^{5+}$	49.7[a]
$DMA^{-4} + Ca^{2+} = CaDMA^{-}$	4.66[c]	Solubility constants calcite	
$Epi\text{-}HMA^{-3} + Fe^{3+} + H_2O =$		$CaCO_3 = Ca^{2+} + CO_3^{2-}$	−8.48[a]
$Fe(OH)Epi\text{-}HMA^{-} + H^{+}$	17.25[c]	Ferrihydrite	
$Epi\text{-}HMA^{-3} + Ca^{2+} = CaEpi\text{-}HMA^{-}$	5.63[c]	$Fe(OH)_3 + 3H* = Fe^{3+} + 3H_2O$	3.55[d]
$HDFO\text{-}B^{2-} + Fe^{3+} = FeHDFO\text{-}B^{+}$	32.02[a]	"soil iron oxide"	
$FeDFO\text{-}B + H^{+} = FeHDFO\text{-}B^{+}$	10.40[a]	$Fe(OH)_3 + 3H* = Fe3^{+} + 3H_2O$	2.70[e]
$FeHDFO\text{-}B^{+} + H^{+} = FeH_2DFO\text{-}B^{2+}$	0.68[a]	Goethite	
$FeDFO\text{-}B + H^{+} = FeHDFO\text{-}B^{+}$	10.40[a]	$FeOOH + 3H* = Fe3^{+} + H_2O$	0.36[b]
$HDFO\text{-}B^{2-} + Ca^{2+} = CaHDFO\text{-}B$	3.52[a]	Henry's law constant	
$Ferrichrome^{3} + Fe^{3+} = FeFerrichrome$	31.05[a]	$CO_2(g) + H_2O = H_2CO_3*$	−1.46[a]
$FeFerrichrome + H^{+} =$	1.5[a]		
$FeHFerrichrome^{+}$			

[a]Martell *et al.* (2001).
[b]Parker and Khodakovskii (1995).
[c]Murakami *et al.* (1989).
[d]Schindler *et al.* (1963).
[e]Lindsay (1979).
[f]RA: Rhodotorulic acid.

addition of 1:1 mole ratio of Fe(III) and rhodotorulic acid could lead to oversaturation of ferrihydrite near neutral pH, depending on the total Fe(III) concentration.

An example for a fungal siderophore with relatively low affinity and specificity for iron is rhizoferrin. In a calcareous soil, rhizoferrin will be even less competitive for iron complexation due to its relatively high affinity for calcium. Ferrichrome, DFO-B, and coprogen are trihydroxamate siderophores. Coprogen has a higher affinity for iron compared to DFO-B. Despite its high stability, Hördt *et al.* (2000) found higher uptake of iron in the presence of the coprogen complex compared to the DFO-B complex by cucumber (strategy I) and maize (strategy II). They hypothesized that the higher uptake was due to faster ligand exchange kinetics of the coprogen complex. Unfortunately, the corresponding ligand exchange rates are unknown.

Iron complexes with humic substances are also important sources for strategy II iron acquisition. Cesco *et al.* (2000) showed qualitatively that

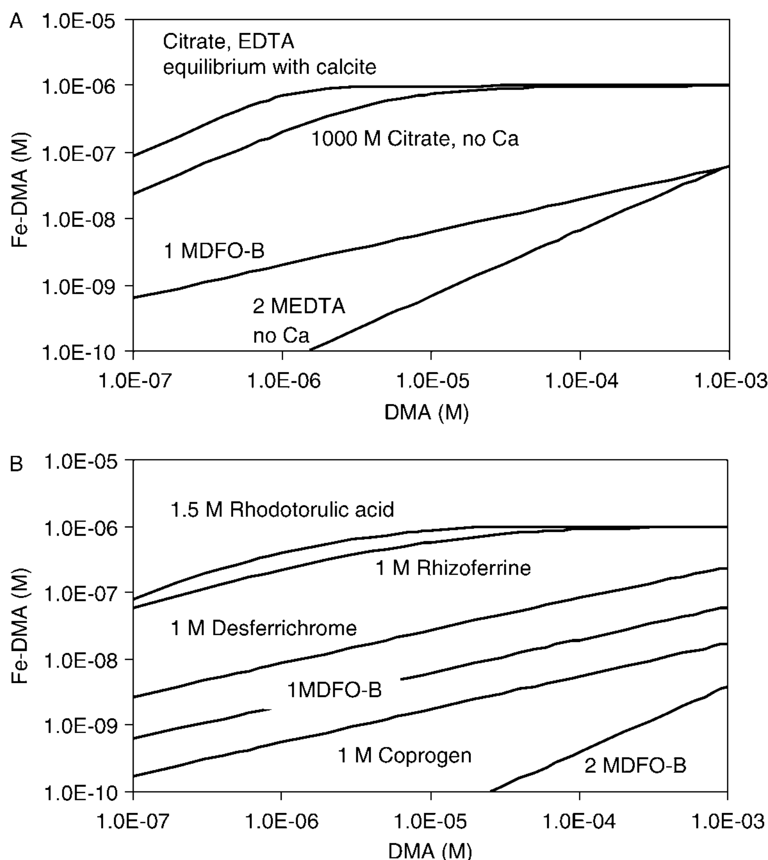


Figure 8 Equilibrium concentration of Fe–DMA complexes as a function of DMA concentrations in the presence of 1 μM Fe(III) and various ligands. Ligand concentrations are sufficient to prevent ferrihydrite precipitation. (A) Competing ligands: 1 μM DFO-B, 2 μM EDTA, or 1000 μM citrate. All calculations in the absence of calcium or in equilibrium with calcite at elevated rhizosphere CO_2 partial pressure. (B) Competing ligands (all bacterial and fungal siderophores): 1 or 2 μM DFO-B, 1 μM coprogen, 1 μM desferrichrome, 1 μM rhizoferrin, or 1.5 μM rhodotorulic acid. No calcium present. Equilibrium constants and solubility products are listed in Tables IV and V. All calculations at pH = 6.8, MP_{CO_2} = 8%, and I = 0.1 M.

HMA sequestered iron from a water extractable humic substances–Fe complex by ligand exchange. Solinas (1994) reacted the microbial siderophore DFO-B with Fe(III)–saturated soil humic acid. After 24 h reaction time, he found all soluble DFO-B as iron complex. However, significant partitioning of DFO-B into humic substances decreases the mobility of the siderophore in soil solution (Higashi *et al.*, 1998; Powell *et al.*, 1982; Solinas, 1994). Unlike most known siderophores, free DFO-B and the Fe–DFO-B complex are positively

charged below pH 10 so that an electrostatic driving force may contribute to the interaction of this particular siderophore with humic substances.

2. Ligand Exchange Kinetics

To evaluate the degree of kinetic limitation of a process, it is useful to compare the half-life of the process in question with a reference timescale. In the case of ligand exchange between an iron shuttle and phytosiderophores, the reference timescale is given by the diurnal exudation cycle of siderophores. It has been demonstrated that iron-uptake rates are high during the period of high siderophore exudation and low otherwise (Cesco *et al.*, 2002; Yehuda *et al.*, 1996), although the efficiency of the Fe–phytosiderophore uptake system remains constant over the day (Alam *et al.*, 2004).

Assuming that the diurnal exudation cycle provides a reference timescale for iron acquisition processes, the half-life of the exchange reaction should not significantly exceed the period of elevated phytosiderophore release. Very slow metal- and ligand-exchange reactions exceeding this reference timescale could limit iron acquisition.

A classic study of kinetic control of a geochemical process in this context is the double-exchange reaction of copper between EDTA and humic substances in the presence of calcium (Hering and Morel, 1989).



$$\text{Ca}-\text{EDTA} + \text{Cu}-\text{humate} \leftrightarrow \text{Cu}-\text{EDTA} + \text{Ca}-\text{humate} \tag{13}$$

The rate of this double-exchange reaction was significantly slower than the rate of the corresponding ligand-exchange reaction in the absence of calcium (Hering and Morel, 1989):



$$\text{EDTA} + \text{Cu}-\text{humate} \leftrightarrow \text{Cu}-\text{EDTA} + \text{humate} \tag{14}$$

In contrast to EDTA, phytosiderophores and most microbial siderophores (with the known exception of carboxylate siderophores such as rhizoferrin) (Shenker *et al.*, 1996) have a low affinity for calcium complexation. Equilibrium calculations of DFO-B and phytosiderophore speciation in equilibrium with calcite at high P_{CO_2} and in the absence of competing ions (other than H^+) predict that the calcium complexes are minor species compared to (partially) protonated free siderophore species. In the light of the observations by Hering and Morel (1989), it appears that the specificity of siderophores for iron is a prerequisite for their utility in biological iron acquisition not only from a thermodynamic standpoint but also from a kinetic perspective.

In the context of strategy II iron acquisition, we will therefore limit the discussion on exchange reactions of the type:



$$PS + Fe{-}L \leftrightarrow Fe{-}PS + L \tag{15}$$

where PS is the phytosiderophore and L stands for organic acids, humic substances, and microbial siderophores. EDTA is a synthetic aminocarboxylate ligand (like mugineic acids) with similar affinity if not specificity for iron as phytosiderophores. In contrast to phytosiderophores, EDTA has been the subject of many detailed studies of ligand-exchange reactions. Therefore, we consider EDTA a useful model compound for phytosiderophores as long as competing transition metal ions or alkaline-earth metal ions are not present.

Reaction 15 may proceed via an adjunctive or a disjunctive pathway (Hering and Morel, 1990):

Disjunctive	Adjunctive
Fe–L → Fe + L	PS + Fe–L → PS–Fe–L
PS + Fe → Fe–PS	PS–Fe–L → Fe–PS + L

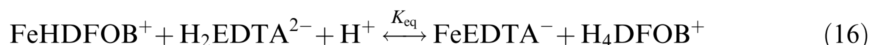
where the disjunctive pathway is initiated by the complete dissociation of the initial complex and the adjunctive pathway involves the formation of a ternary complex of the outgoing and incoming ligands with iron.

The rate of ligand-exchange reactions depends on the nature and concentrations of the incoming and outgoing ligands. Bell *et al.* (2005a) used ethylenediamine-di(*o*-hydroxyphenylacetic acid) (EDDHA) as a model ligand for phytosiderophores to exchange various ligands from their corresponding iron complexes. They found increasing exchange rates in the order of EDTA < HEDTA < citrate < NTA as outgoing ligand. While exchange reactions between EDDHA and the Fe–NTA complexes reached equilibrium within 4 h (which approximately corresponds to the timescale of diurnal phytosiderophore exudation), the reaction with Fe–EDTA complexes was still far from equilibrium after 2 days of reaction time.

3. Ligand Exchange Between Phytosiderophores and Microbial Siderophores

Very slow exchange kinetics are observed in reactions involving the release of iron from microbial siderophores. For example, iron exchange between equimolar concentrations (1 μM) of DFO-B and ferrichrome A (both microbial siderophores) at pH 7.4 with a 5% excess of DFO-B over iron had a half-life of more than 1000 h (Tufano and Raymond, 1981)! While the rates

and mechanisms of ligand exchange between DFO-B and phytosiderophores are not known, it is instructive to consider the corresponding reactions involving EDTA. The iron transfer from DFO-B to EDTA was extensively studied, as a model for intracellular iron release from siderophores in microbial iron acquisition (Albrecht-Gary *et al.*, 1995; Biruš *et al.*, 1998; Hördt *et al.*, 2000; Monzyk and Crumbliss, 1981, 1983; Tufano and Raymond, 1981) or for ligand exchange by phytosiderophores (Hördt *et al.*, 2000).



$$\mathrm{FeHDFOB^{+} + H_2EDTA^{2-} + H^{+} \overset{K_{eq}}{\longleftrightarrow} FeEDTA^{-} + H_4DFOB^{+}} \tag{16}$$

The ligand-exchange reaction proceeds via an adjunctive pathway involving the successive exchange of hydroxamate groups and formation of an intermediate ternary complex, followed by complete exchange of coordination (Biruš *et al.*, 1993). Tufano and Raymond (1981) have parameterized a rate law for this exchange reaction:

$$V_{\mathrm{initial}} = \frac{\mathrm{d}\left[\mathrm{FeHDFO^{+}}\right]}{\mathrm{d}t} = \frac{k_1 k_2 \left[\mathrm{FeHDFO^{+}}\right]\left[\mathrm{H^{+}}\right]\left[\mathrm{H_2EDTA^{2-}}\right]}{k_{-1} + k_2\left[\mathrm{H_2EDTA^{2-}}\right]} \tag{17}$$

where V_{initial} is the initial rate (M s^{-1}), k_1 (M^{-1} s^{-1}) and k_{-1} (s^{-1}) are the forward and reverse rates of unwrapping/protonation of the first hydroxamate group of the Fe–DFO-B complex, and k_2 (M^{-1} s^{-1}) is the overall rate constant of the ligand-exchange reaction. At $I = 0.2$ M (KNO_3), 25°C, and pH 5.4, they found $k_{-1} = 34$ (s^{-1}), $k_{-1} = 3.4$ (s^{-1}), and $k_2 = 200$ (M^{-1} s^{-1}).

Emulating rhizosphere conditions, we can use the rate law to calculate initial ligand exchange rates of approximately 0.01 μM h^{-1}, assuming initial concentrations of 1 μM Fe–DFO-B complex and 500 μM EDTA at pH 5.4. Noting that the observed initial rates decreased with increasing pH (Tufano and Raymond, 1981), we can conclude that the ligand exchange process is slow compared to timescales of diurnal exudation of phytosiderophores. Somewhat faster ligand exchange kinetics have been observed for siderophores having catecholate and α-hydroxycarboxylate functional groups (Albrecht-Gary *et al.*, 1995).

Low-molecular weight ligands, such as mono-hydroxamates (Monzyk and Crumbliss, 1983) and oxalate (Biruš *et al.*, 1998), can catalyze the ligand-exchange reaction between Fe–DFO-B and EDTA. It may casually be noted that such low-molecular weight ligands are present in the rhizosphere and their exudation by iron-stressed strategy II plants (Fan *et al.*, 1997, 2001) may serve to increase the rates of ligand-exchange reactions. In summary, not only the thermodynamics, but also the rates of ligand-exchange reactions under rhizosphere conditions need to be considered in plant iron acquisition.

Mono- and dihydroxamate siderophores can undergo ligand-exchange reactions via several pathways (Boukhalfa and Crumbliss, 2002). Hördt *et al.* (2000) observed fast iron transfer from iron coordinated by a mixture of mono- and dihydroxamate degradation products of coprogen to EDTA or epi-HMA, demonstrating that biodegradation of microbial siderophores facilitates ligand exchange from a thermodynamic and a kinetic standpoint.

4. Ligand Exchange Between Phytosiderophores and Humic Substances

As discussed earlier, iron bound to water-soluble humic substances is taken up by strategy I and II plants (Cesco *et al.*, 2002). Observations of diurnal variations in uptake by strategy II plants indicate that iron is released from the NOM by a ligand-exchange reaction. This is supported by direct observations of ligand exchange to mugineic acid (Cesco *et al.*, 2000).

Rocha *et al.* (2002) observed ligand exchange between humic substances at natural Fe-concentration levels (350–450 μmol g^{-1}) with 1.27 mM diethylenetetraaminepentaacetic acid (DTPA) or 1.71 mM EDTA at pH 4.5. They found that 55% or 51% of the total iron was DTPA or EDTA available and more than 8 h were required to reach exchange equilibrium but less than 1 h was required to exchange 50% of the available pool. Burba and Van den Berg (2004) used humic substances collected at the same site and used the same experimental protocol as Rocha *et al.* (2002) and found EDTA availability of 98% and a release kinetic that was characterized by a fast release with a half-life of 50 min in which 90% of the available iron was released, and a slow step with a half-life of 650 min. Gu *et al.* (1995) reacted humic substances at natural Fe concentration levels (185 μmol g^{-1}) with 100 μM EDTA at pH 4 and found that exchangeable Fe was released in a ligand-exchange reaction with a half-life of 8.2 min.

Considerably slower exchange kinetics were observed at pH 8 using an immobilized chelator (Burba, 1994). The Fe exchange kinetics was characterized by a fast exchange reaction in which a small percentage of iron was exchanged during the first 3 h, which was followed by a slow exchange reaction with a half-life of about 24 h. About 86% of the total iron was exchangeable. Nevertheless, these results indicate that ligand-exchange reaction between humic substances and other ligands is fast enough to make at least a fraction of this iron pool available for plant uptake.

5. Ligand Exchange in the Apoplasm

Solutes can freely diffuse into the outer layers of the root cortex, the apoplasm. Diffusion proceeds in the pore space between plant cells, the

apoplastic space. The central part of the root, including the xylem and phloem are isolated from the apoplasm by the impermeable casparian strip. The main route of transport through the casparian strip is by crossing cell cytoplasmic plasmalemma membrane through membrane-bound transport systems. Alternatively, diffusion through breaks of the casparian strip at budding lateral routes or damaged roots may occur.

The apoplasm has a net negative charge and possesses ligating functional groups resulting in an electrostatic and directional binding of iron. Iron carriers can release iron to the apoplasm, creating an apoplastic iron pool that can serve as an iron source to strategy II iron acquisition (Zhang *et al.*, 1991a, 1999). The apoplastic iron pool decreases during the time of maximum siderophore exudation (in the morning) and recovers until the next morning (Alam *et al.*, 2004). This indicates that the reference timescale for ligand-exchange reactions between iron carriers and the apoplasm is essentially 24 h, whereas the reference timescale for ligand exchange between phytosiderophores and the apoplasm corresponds to the period of maximum siderophore release.

A study that has been already discussed earlier investigated the ligand-exchange rates between an aquatic Fe–humic acid complex and a receiving chelating ion exchanger on cellulose basis (Burba, 1994). This system can serve as a model for apoplastic iron loading by humic substances. They found that the ligand-exchange reaction proceeds by a disjunctive mechanism where the release of iron by the humic acid complex was rate determining. The Fe exchange kinetics was dominated by a slow exchange reaction with a half time of about 24 h. This result seems to indicate that humic substances may facilitate apoplasm loading from a kinetic standpoint.

Zhang *et al.* (1991a) investigated apoplasm loading (wheat) by addition of 5 μM iron to nutrient solutions for 5 h during the dark period. They applied inorganic iron (i.e., ferrihydrite), and iron complexed to rhodotorulic acid (see Fig. 5 and Table IV), DFO-B, and EDDHA, respectively. The resulting apoplastic iron concentrations and corresponding translocation rates during the day were high in experiments where iron was supplied in the form of hydroxide or rhodotorulic acid complex, and low when it was supplied as either the DFO-B or EDDHA complex. The relative low efficiency of DFO-B and EDDHA complexes for iron nutrition via the apoplasm may reflect their slow exchange kinetics and/or their high thermodynamic stability.

VII. CONCLUSIONS AND OUTLOOK

The exudation of siderophores by chlorotic graminaceous plants is part of a highly efficient iron acquisition process. The presence of siderophores in the rhizosphere triggers a range of complex soil chemical processes including

ligand exchange, dissolution, and transport. In the past, most studies on iron dissolution have considered the reactions of iron minerals with individual ligands. New research, however, shows that organic acids and siderophores may interact synergistically to cause iron dissolution. Equilibrium models have been very useful for understanding the driving forces and direction for dissolution and precipitation reactions. Nonetheless, kinetic processes are a major constraint in the mobilization of iron and exchange between different ligands. A full understanding of plant iron acquisition requires the detailed knowledge of the rates and mechanisms of these processes.

In recent years, much progress has been achieved in the understanding of the molecular biology of iron acquisition. Various transporters for root iron uptake have been identified and their regulation is a subject of active research (Bauer *et al.*, 2004; Curie and Briat, 2003; Grotz and Guerinot, 2003; Reid and Hayes, 2003; Schaaf *et al.*, 2004; Schmidt, 2003). Concurrently, applied research in Fe-deficiency diagnosis and remediation considering agricultural and horticultural management practices have become critical to the efficiency and economic viability of food production (Abadía *et al.*, 2004; Jolley *et al.*, 2004). The soil is the ultimate target of important plant physiological iron-deficiency responses and is a mediator for many agricultural remediation strategies for Fe deficiency. Therefore, we hope that this overview of soil chemical aspects of plant iron acquisition will serve as a useful reference for scientists working in these exciting fields.

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Taking Stock of the Brazilian "Zero-Till Revolution": A Review of Landmark Research and Farmers' Practice

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Advances in Agronomy, Volume 91

0065-2113/06 $35.00
DOI: 10.1016/S0065-2113(06)91002-5

Two decades of extensive research and experimentation with zero-till methods has allowed "ideal" zero-till systems to emerge in Brazil, involving no soil turning, maintenance of a permanent vegetative cover, and rotations of both cash and cover crops. By exploiting rapid successions of suitable crops, for example, as well as through careful temporal and spatial planning, Brazilian examples show that it is possible to continuously cover soil, gradually increase soil organic matter (SOM) stocks, integrate livestock, move surface-applied lime through the soil profile, break compact soil layers, and reduce reliance on agrochemicals in zero-till, all under a variety of edaphic and climatic conditions, and levels of mechanization/farm sizes. Various such technologies and systems are reviewed in this chapter. However, we also note that among smallholder zero-till farmers, for example, the adaptations of "ideal" zero-till systems are manifold and complex, partial adoption of certain components and technologies rather than full adoption of zero-till systems being the norm. By examining farmers' experiences and practice, we ascertain that in many cases there is perhaps a divorce between the ideal, originating mainly from individual technology research on agricultural research stations, and farmers' reality, given the complexity of socioeconomical constraints facing the latter. We conclude that although there is a wealth of valuable zero-till experience and technologies precipitating from the Brazilian zero-till "revolution," numerous challenges in zero-till research, especially in respect to resource-poor smallholder farmers, still remain, and perhaps more holistic, participatory and adaptive on farm-research is necessary in future.

ABBREVIATIONS

APDC	Zero-till Organization of the Cerrado
CEC	Cation exchange capacity
CIRAD	French Agricultural Development Corporation
EMATER	Government agricultural extension services
EMBRAPA	Brazilian Agricultural Research Corporation
EPAGRI	Agronomic Institute of Santa Catarina
FEBRAPDP	Brazilian Federation for Direct Planting into Straw
GTZ	German Development Corporation
IAPAR	Agronomic Institute of Paraná
ICI	Imperial Chemical Industries
IPEAME	Agricultural Research Institute of Southern Brazil
IPW	Integrated weed management
POM	Particulate organic matter
SOC	Soil organic carbon
SOM	Soil organic matter

I. INTRODUCTION

Effectively brought about with the commercial release of the herbicides atrazine and paraquat and the subsequent production of the first mechanized zero-till planters by "Allis Chalmers" in the late 1950s and early 1960s (Hill *et al.*, 1994; Séguy *et al.,* 1996), modern zero-till, defined in this chapter as the planting of crops in previously unprepared soil by opening a narrow slot, trench, or band of sufficient width and depth to obtain proper seed coverage, without performing any other soil preparation (Phillips and Young, 1973), has become increasingly recognized as a means of improving agricultural soil and water conservation, of gradually building soil fertility, of reducing labor/fuel requirements and machinery wear, and concomitantly increasing overall farm profitability (Belvins and Frye, 1993; Borlaug, 2000; FAO, 2001). However, under certain circumstances, such benefits may only accrue partially or not at all, while some drawbacks may precipitate. Given the lack of mechanical weed and pest habitat clearing, for example, as well as the slower soil organic matter (SOM) mineralization and consequent nutrient release in unplowed compare to plowed soils, zero-till is also commonly associated with heavy reliance on agrochemicals and biocides to replace some of the functions of plowing. Furthermore, it is frequently maintained that zero-till entails sophisticated machinery capable of seeding through residues into unworked soil and evenly spreading harvest trash, as well as advanced managerial skills in order to optimize machinery, input, labor, and crop use (Brunner *et al.*, 1998; Dijkstra, 2002; Russel, 1998), thereby potentially being less suitable for asset-restricted smallholder farmers, farmers who often suffer most from the consequences of poor soil fertility and soil degradation. Additionally, zero-till is commonly assumed problematic or unfeasible in areas with shallow, acidic, or extreme-textured soils (sands or heavy clays) with a propensity to compact, without good internal drainage (Derpsch, 2001), on hilly topography, and/or in areas without sufficient rainfall for ample biomass production (Brunner *et al.*, 1998; Lal, 1993).

Nevertheless, despite such challenges and owing to its significant and well-documented advantages in a host of different regions, zero-till has become progressively more widespread throughout the world, most notably in countries such as the United States, Brazil, Argentina, Canada, and Australia, expanding to an area of over 72 million hectares globally according to some of the most recent estimates (Derpsch and Benites, 2004). Brazil in particular, where the area estimated under zero-till-type land management has exploded from less than 1000 ha in 1973/1974 to nearly 22 million hectares in 2003/2004 (FEBRAPDP, 2004) is a case *par excellence* of successful zero-till dissemination and adoption [*N.B.*, these adoption data are the only available and a result of a compilation of information provided by

extension services and zero-till associations in individual Brazilian states, and, as Ribeiro *et al.* (2005) further point out may also include systems where cover crop seed is broadcast and incorporated with a disc harrow rather than drilled, and so on].

Although zero-till adoption in Brazil initially started on mechanized farms in humid subtropical Southern Brazil, on medium-textured, well-fertilized, and limed soils on flat to undulating land with low-weed pressure, it has since spread and reportedly proved successful on a large range of soil textures (from <10% to >70% clay) (Amado and Reinert, 1998; Amado *et al.*, 2006), on lithic or gravelly land with steep slopes (Freitas, 2000; Pieri *et al.*, 2002), for farmers without expensive machinery and capital inputs (Freitas, 2000; Heiden, 1999; Melo, 2000; Samaha *et al.*, 1996, 1998) or agrochemical outlays (Petersen *et al.*, 1999; Saturinino and Landers, 1997), and in regions that encompass the elevated, year-round humid subtropics to the acidic, seasonally dry tropical savannah plateau (cerrado) of Central Brazil. Forty-five percent of total cultivated land in Brazil is now estimated to be managed with zero-till (Scopel *et al.*, 2004), although in Southern Brazil, this figure is reported to exceed 80% (Amado *et al.*, 2006) or even 90% in the case of land cropped by smallholders (<50 ha) (Denardin and Kochhann, 1999). Among the leading zero-till nations, Brazil is purportedly the only one with both substantial zero-till in the tropics, as well as, importantly, a significant amount of smallholder zero-till farms (Ralisch *et al.*, 2003; Wall and Ekboir, 2002). The latter is perhaps of particular significance, as, contrary to zero-till spread in general, the adoption of true (permanent rather than sporadic) zero-till systems by smallholder farmers worldwide has been poor, remaining relatively marginal outside Brazil, Paraguay (where appropriate systems spread to from Southern Brazil), and small parts of Central America, where similar systems were already traditional (Buckles *et al.*, 1998). While the opportunity cost of labor and land and/or residues is often viewed as a stumbling block to smallholder zero-till, Berton (1998) suggests that the main reasons for smallholder farmers in Southern Brazil to adopt zero-till practices include labor and time savings, erosion control, greater income, and higher yields. Ribeiro and Milléo (2002) concur, specifying that labor savings and less drudgery, once plowing and mechanical weeding are discontinued, are the major incentives expressed by smallholder farmers.

In summary, numerous reports highlight a large diversity of highly productive, profitable, and labor-reducing farms in Brazil, ranging in size and scope from low-capital, family operated, semisubsistence smallholdings (<50 ha) to large, capital-intensive, and commercially orientated agricultural enterprises (Ambrosi *et al.*, 2001; Berton, 1998; Darolt, 1998a; Fontaneli *et al.*, 2000; Rego, 1998; Ribeiro and Milléo, 2002; Scopel *et al.*, 2003; Wall, 1993), and therefore ostensibly a wealth of diverse zero-till experiences that

could potentially prove useful in other parts of the world has accumulated across Brazil, both at agricultural research stations and universities, but also among Brazilian farmers, some of which are now into their third decade of practicing zero-till-type land management. However, although much of this knowledge and experience is intrinsic in Brazil and neighboring countries, a large amount remains locked in local literature and conference proceedings rather than being published internationally, due partially to the Portuguese–English language barrier. Some recent English-language reviews do exist, but these either focus on certain specific aspects of Brazilian zero-till (Bernoux *et al.*, 2006; Machado and Silva, 2001, on soil management; on soil carbon sequestration and erosion), are intended to give a general overview rather than agronomic/technical detail (Scopel *et al.*, 2004), or focus on a certain region within Brazil (Freitas, 2000, on smallholders in Santa Catarina State). The broad objective of this chapter is consequently to first review some of knowledge precipitating from Brazilian zero-till experiences, this mainly coming from empirical research, and then, where possible given the relative dearth of truly analytical data in this respect, critically take stock of it by putting it into the context of farmers' practice. The particular focus of the chapter is on overcoming some of the major agroecological challenges associated with productive zero-till systems, such as effectively managing permanent soil cover, soil fertility, weeds and pests without all-out reliance on agrochemicals, integrating livestock, and suitable equipment for various soils, slopes, and levels of mechanization. Special emphasis will be granted to the context of resource-poor smallholder farmers.

II. HISTORICAL BACKGROUND

The history of the Brazilian zero-till "revolution" is well documented in the literature. Calegari (1998b), Derpsch (1998), Landers (2001), Steiner *et al.* (2001), and Ekboir (2002), among others, provide recent and comprehensive English-language accounts of the development of zero-till in Brazil. In brief (more detailed histories are provided in a later section), zero-till development precipitated out of the widespread soil degradation in the 1960/1970s in subtropical Southern Brazil (especially Paraná), and spread from here to Paraguay and the tropical Brazil in the early 1980s (Fig. 1).

A. Zero-Till Development in Subtropical Southern Brazil

During the 1960s, a significant expansion of the area under soybean (*Glycine max* L. Merr) and winter wheat (*Triticum aestivum* L.) occurred in Southern Brazil. The intensive plowing and disking, residue burning and

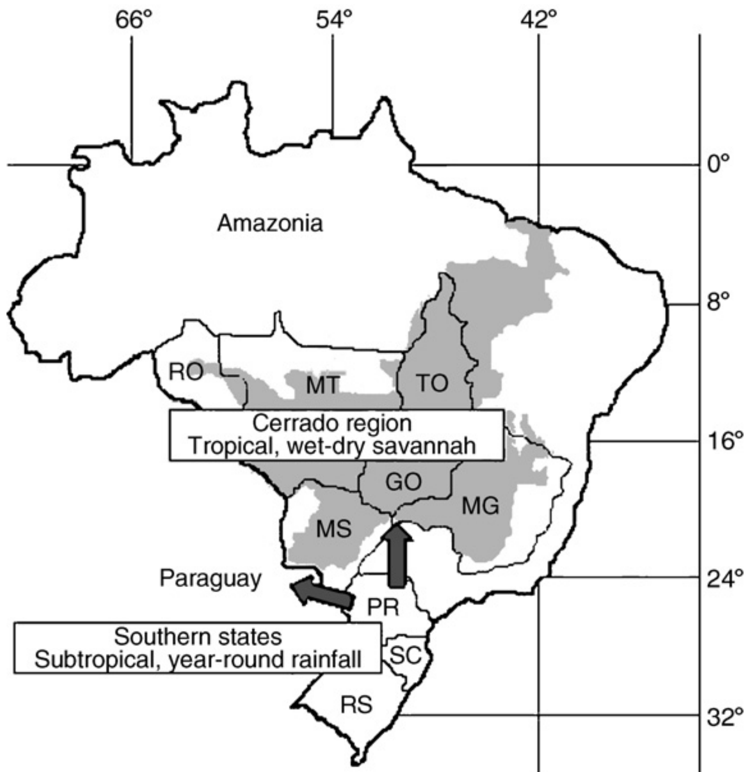


Figure 1 Map of Brazil showing the subtropical southern states of Paraná (PR) and Rio Grande do Sul (RS), where Brazilian zero tillage originated and then spread west and north (indicated by arrows) to Paraguay and the tropical "cerrado" savannah region (shaded). RO, Rondônia; MT, Mato Grosso; TO, Tocantins; GO, Goiás; MG, Minas Gerais; MS, Mato Grosso do Sul; SC, Santa Catarina. Typically, farms in the cerrado region are large and mechanized, while in Southern Brazil a great variety of farm sizes and levels of mechanization exist.

downhill seeding regimes widely adopted with these crops exposed bare soils to intensive rainfall, which in turn led to extensive soil erosion and concomitant economic losses throughout large tracts of Southern Brazil (Borges, 1993; Cogo *et al.*, 1978; Gianluppi *et al.*, 1979; Mielniczuk and Schneider, 1984). Cassol (1984) estimated that during the 1980s, two-thirds of agricultural land in Southern Brazil showed some form of degradation, often manifested in the loss of SOM, poor rainfall infiltration, structural degradation and compaction, and a reduction in plant available water, but also in the pollution of waterways through runoff and erosion and even the abandonment of farms (Amado and Reinert, 1998; Pöttker, 1977). Although farmers frequently put up terraces and contours in an attempt to check

runoff and topsoil loss, this rarely curtailed erosion sufficiently, and Mielniczuk (2003) estimated that for each kilogram of soybeans harvested, 10 kg of soil were lost. In response, concerned farmers and researchers gradually began to shift their production paradigm toward promoting better *in situ* soil conservation. The first scientific zero-till trial was initiated in 1969 by the Federal University of Rio Grande do Sul on a 1-ha plot, but discontinued in the second season due to the accidental destruction of the zero-till planter used for the trial (Borges Filho, 2001). New trials were established in 1971 at research stations in Londrina and Ponta Grossa in the state of Paraná by the Agricultural Research Institute of Southern Brazil (IPEAME, later EMBRAPA) in collaboration with the GTZ and subsequently also ICI (Derpsch, 1998; Steiner *et al.*, 2001). Impressed by the results of a zero-till demonstration plot set up on his farm, Herbert Bartz, a farmer in Rolândia, northern Paraná, visited zero-till research facilities at the ICI headquarters in Fenhurst, UK, and Harry Young in Kentucky. Bartz subsequently returned to Brazil with a zero-till planter and planted his first zero-till soybean crop in October 1972. His success in controlling erosion and reducing production costs quickly inspired some neighbors to adopt similar technologies. The successful diffusion of zero-till systems on a broader scale, however, remained erratic throughout the 1970s, due mainly to the lack of suitable techniques to effectively control weeds, as well as of planters able to work with high amounts of residues, of appropriate cover crop options, of technical assistance and studies clearly demonstrating the advantages of zero-till (Amado and Reinert, 1998; Bernoux *et al.*, 2006). Derpsch (1998) elaborates that the first Brazilian-built planters (available from 1975/1976 and based on a rotary hoe) were slow and cumbersome, while the only the herbicides 2,4-D and paraquat were available for weed management.

The release of glyphosate in Brazil in the mid-1970s changed this situation significantly, and toward the beginning of the 1980s, farmers began to organize themselves into zero-till-promoting associations, such as the "Clube da Minhoca" ("Earthworm Club") and the "Clubes Amigos da Terra" ("Friends of the Soil" clubs), as well as private research institutions, such as the "Fundação ABC" (ABC Conglomerate of Farmers' Cooperatives), thereby becoming more apt at voicing concerns within the public arena. The provincial agricultural research institution of Paraná, IAPAR, became the first government institution to intensify and spearhead systematic research into zero-till systems (Borges Filho, 2001; Dijkstra, 2002). Gradually, zero-till development received increased backing from multinational agrochemical corporations, international development agencies, local seed, and agricultural machinery companies (Busscher, 1996), as well as the national Brazilian Agricultural Research Corporation, EMBRAPA, who established breeding programs to enhance various crops' suitability to zero-till conditions (Scopel *et al.,* 2004).

The local government extension service, EMATER, however, did not support and recommend zero-till technologies until the late 1980s, and the initial expansion drive of the zero-till was in essence led by pioneer farmers, who also organized the first Brazilian zero-till conference in 1981 (Steiner *et al.*, 2001). Zero-till technologies and systems subsequently spread fairly rapidly from Paraná to other Southern Brazilian states and neighboring Paraguay, where similar environmental conditions existed.

B. Zero-Till Development in Tropical Brazil

During the 1980s, the tropical, wet-dry savannah region (cerrado) of Central Brazil emerged as the fastest growing agricultural frontier zone of Brazil, experiencing a boom of continuous soybean and cotton monocultures due to favorable world market prices for these crops (Séguy *et al.*, 1996). However, similar to Southern Brazil, conventional agricultural practices in this region led to significant soil degradation. Séguy *et al.* (1996) report yield potential declines in degraded soils despite the increased use of chemical inputs and the replacement of monocropping by crop rotations, while in some regions SOM stocks were being depleted by as much as 30–50%. A steady interregional migration of farmers from Southern Brazil to tropical Brazil brought a transfer of the basic zero-till principles in its wake, but the different agro-ecological conditions of humid subtropical Southern Brazil compared to those of frost-free, seasonally dry, tropical Brazil, as well as the often quite different scale of large cerrado farms compared to generally smaller farms in the South meant that zero-till systems still had to be undergo considerable modification before being effective in the latter region (Spehar and Landers, 1997). The first records of mechanized zero-till in the tropics of Brazil, and probably worldwide, were in the state of Goiás dating from 1981/1982 (Landers *et al.*, 1994), although Landers (1998) does recount that smallholder farmers in the state of Rondônia, Center-West Brazil, were zero-tilling beans (*Phaseolus sativa* L.) with manual jab planters into rice straw after managing weeds with paraquat already in about 1980. The French Agricultural Development Corporation, CIRAD, collaborating with pioneer farmers and local organizations, became instrumental in the process of developing suitable zero-till systems for the cerrado region from around 1986 (Landers, 1998). Working simultaneously on improving the cropping system and crop germplasm, CIRAD and its partners in Mato Grosso state, for example, were able to develop several highly productive rain-fed rice cultivars suitable for zero-till, such as CIRAD 141 and Sucupira (Séguy and Bouzinac, 2001), as well as devising systems that could successfully integrate livestock herds with cropping enterprises (Séguy *et al.*, 1996). With the results from the CIRAD-led research, as well as official and private

sector herbicide research and new developments in zero-till planters, enough information specific to the cerrado was generated to allow zero-till to be promoted on a general level throughout the region (Landers, 1998). The cerrado region is now the major expansion area of zero-till in Brazil, with over 6 million hectares estimated under zero-till in 2002 (APDC, 2005). Landers (1998) contends that possible future zero-till expansion will encompass agricultural areas in the Amazon region, while Bernoux *et al.* (2006) report that enticed by high-potential profit margins, ranchers in Amazonia have already started converting pasture into soybean/millet (*P. americanum* L.) zero-till cropping systems.

C. Development of Smallholder Zero-Till Systems

Up until the mid-1980s, Brazilian zero-till research was almost exclusively directed toward medium to large-scale (>100 ha), mechanized farms, especially as these contributed most to the erosion process (Steiner *et al.*, 2001). Although smallholder (<50 ha) farmers in Southern Brazil also frequently expressed concern about soil erosion, the availability of zero-till technologies and equipment suited to their situations, as well as a technical support and farmer training, was limited at this stage (Berton, 1998). In the second half of the 1980s, IAPAR started focusing research efforts on resource-poor farmers, and in cooperation with the newly established Brazilian Federation for Direct Planting (FEBRAPDP) and the government extension service EMATER commenced a drive to introduce zero-till technologies on smallholder farms through demonstrations, seminars, field courses and training days. Light-mechanization (minitractors) and animal-drawn zero-till equipment was developed and trialed on various soils and topography by IAPAR and its equivalent in the state of Santa Catarina, EPAGRI (Table I), and gradually more and more smallholder farmers started adopting zero-till technologies.

However, as the results of a recent survey in the Irati region of Paraná indicate, unlike their more commercially orientated larger-scale counterparts, smallholder zero-till farmers without sufficient means to buy recommended external inputs and consequently often a high degree of risk-adverseness, as well as high-opportunity costs for land, labor, and crop biomass, still resort to a range of intermediate-tillage systems rather than adopting complete or "ideal" zero-till models promoted by research and extension (Palmans and van Houdt, 1998; Ribeiro *et al.*, 2005). Many such farmers fall back on disc harrowing before/after certain crops in order to check weeds and pests and incorporate lime, while sometimes neglecting cover and main crop rotations that could potentially optimize the functioning of zero-till systems. As Ribeiro *et al.* (2005) further conclude, contrary to

Table I
The Development, Testing and Trialing, and Dissemination and Adoption Process of Zero-Till Technologies for Smallholder Farmers in Santa Catarina State, Southern Brazil (from Freitas *et al.*, 1994)

1984/1985	1986	1987
Facilitation of farmer excursions to relevant research and experimental sites Formation of microcatchment commissions	Establishment of a green manure observation unit and identification of potential cover crop green manure systems	Establishment of the first crop through zero-till with animal traction
1988/1990	**1991/1992**	**1993/1994**
Period of testing and adapting agricultural equipment, especially equipment for zero-till with animal traction and light mechanization	Farmers start to adopt zero-till practices (5% adoption rate) Continuous research and adaptation of zero-till equipment	Increase in the area under zero-till Acquisition of equipment by individuals and farmer groups

some perhaps overly enthusiastic reports on the success of zero-till in Brazil, and although some very-well functioning "ideal" smallholder zero-till farms do exist, numerous challenges in respect to resource-poor smallholder zero-till on a general level still remain. As Calegari (2002) argues, such challenges, but also innovations and advances in terms of smallholder systems (e.g., equipment and fertility changes) need to be continuously evaluated and monitored in testing/validation processes that involve the smallholders themselves. We will elaborate on such challenges and partial adoption issues under the relevant sections.

III. INDIVIDUAL ISSUES, INNOVATIONS, AND CHALLENGES

A. Permanent Soil Surface Cover

In regions that experience high-intensity rainfalls and support undulating terrain and/or erosive soils, protecting the soil from raindrop impact through sufficient vegetative mulch is conceivably one of the best safeguards against excessive runoff and erosion (Amado, 1985; Calegari, 2000, 2002; Erenstein, 2003; Wildner, 2000). Not plowing, in turn, means that a protective biomass cover or mulch from previous crops or spontaneous plants can be maintained on the soil surface. Beyond immediate erosion and runoff control, a soil cover is also important for improving soil moisture maintenance by

reducing evaporation from bare soil (Amado *et al.*, 1990a; Stone and Moreira, 1998, 2000), for mediating soil temperature extremes (Derpsch *et al.*, 1986), for providing a buffer against compaction under the weight of heavy equipment or animals (Séguy *et al.*, 2003), for smothering weeds (Darolt, 1997; Kumar and Goh, 2000), creating a favorable environment for beneficial soil fauna and flora (Balota *et al.*, 1996) and preventing soil and water contamination from pesticides and fertilizers leaching (Scopel *et al.*, 2004), but may also make the planting process more complicated, allow pests and pathogens to reproduce and spread longer in close proximity to crops (Forcella *et al.*, 1994), protract the warming up of soil after cold periods, induce erratic crop germination, and decrease the efficiency of fertilizers and herbicides (Banks and Robinson, 1982; Rodrigues, 1993). Nevertheless, zero-till in itself, without soil cover (for example, if residues are burnt, grazed, or otherwise exported from the field), can lead to worse soil degradation and crop productivity than plowing. Especially where soils are sandy and/or have high-bulk densities/low-total porosities and hence a tendency to form crusts upon wetting and drying, leaving land unplowed and uncovered means that it actually may lose more water and topsoil through runoff than if it were plowed (Bailey and Copeland, 1961; Laryea *et al.*, 1991; Nicou and Chopart, 1979; Scopel and Findeling, 2001; Seganfredo *et al.*, 1997; Shaxton and Barber, 2003; Unger, 1992). The amount of surface sealing or crusting resulting from raindrop impact during a rainfall event is in turn inversely proportional to the amount of vegetation or residues covering the soil, as are consequently infiltration rates over the course of a shower (Calegari, 2002; Roth, 1985; Roth *et al.*, 1987). Infiltration studies with a rainfall simulator in Paraná showed that regardless of tillage system, 100% water infiltration only occurred when soils were completely (100%) covered with plant residues, while bare soils only measured between 20% and 25% water infiltration (Derpsch, 1986). A residue cover of about 4–6 t of dry matter per ha is commonly proposed as adequate for erosion control (Lal, 1982, 1993; Mannering and Meyer, 1963; Roose, 1977), as this is assumed to cover close to 100% of the soil and ensure complete infiltration of rainfall, although this depends on crop species, flatness of the residues, rainfall intensity and duration, soil physical conditions (texture, permeability) and the land slope (Meyer *et al.*, 1970). In Londrina, Paraná, Roth *et al.* (1988) reported that about 7 t of soybean or 4–5 t of wheat residue dry matter per ha would provide 100% soil cover. They further remarked that in Southern Brazil, the average quantities of wheat or soybean residue left on the field after harvest amount to about 1.5 and 2.5 t ha^{-1}, respectively, which would amount to an average degree of cover of only about 60%. Thus, they put forward, in order to control erosion thoroughly, a change from conventional tillage to zero-till in this region must be accompanied by the integration of mulch producing crops or cover crops.

Apart from the physical amount of biomass produced as mulch, two other aspects are important to consider. First, the mulch should be evenly distributed over the plot, with most of above-ground crop residues ideally remaining anchored in the soil. In mechanized systems, harvesting machines should consequently have a device to spread residue trash evenly over the entire cutting edge, but, as Derpsch (2001) laments, this is seldom properly understood by machine manufacturers, the result often being an uneven distribution of plant residues, which in turn exacerbates poor performances of herbicides and seeding equipment. Second, it is also important that the mulch continues functioning as a cover at least until the following crop has itself developed a sufficient canopy to protect the soil. The mulch's degree of resistance to decomposition within a given climatic and edaphic context is in turn chiefly governed by its carbon (C) to nitrogen (N) ratio, but also to a lesser extent by its degree of lignification and its polyphenolic content (Calegari, 2002; Palm and Sanchez, 1991; Seneviratne, 2000), meaning that less mature crop stands and legumes are generally less suited for long-lasting (6-week or more) complete cover. Séguy *et al.* (1992) found that while maize (*Zea mays* L.) and rice (*Oryza sativa* L.) residues still maintained a soil cover of about 20–30% four months after the first rain at the end of the dry season in tropical Brazil, soybean residues had completely disappeared after the third month (Table II).

Rather than rely purely on crop residues from a main crop to provide adequate and permanent soil cover, especially in regions where the climate favors rapid decomposition of residues, one of the major Brazilian adaptations of zero-till has been the strong emphasis on integrating fast-growing winter cover crops and summer crop rotations into zero-till cropping systems. Such crops can be intercropped prior or planted immediately after the harvest of the main crop and rapidly produce abundant mulch, consequently allowing a succession of enhanced, year-round biomass accumulation. This can compensate for residue decomposition, as well as offsetting potential

Table II
Loss of Soil Cover After the Start of the Rainy Season in Western Brazil (Tropical Humid Cerrado Region) (Data from Séguy *et al.*, 1996)

	Soil cover (%)		
Days after first rain	Maize	Rice	Soybeans
30	82	85	35
60	54	46	16
90	30	38	7
120	22	26	0

opportunity costs of residues in their grazing value, for example. Due to the high amount of mulch left on the soil surface at seeding time, Brazilian farmers hence commonly refer to zero-till as "*plantio direto na palha*" or "planting directly into straw" (Amado *et al.*, 2006), and Derpsch (2001) and Steiner *et al.* (2001) argue that the complete integration of cover crops into zero-till cropping systems is probably the single most fundamental key to the success of such systems in Brazil.

B. Cover Crops, and Crop Rotations and Associations

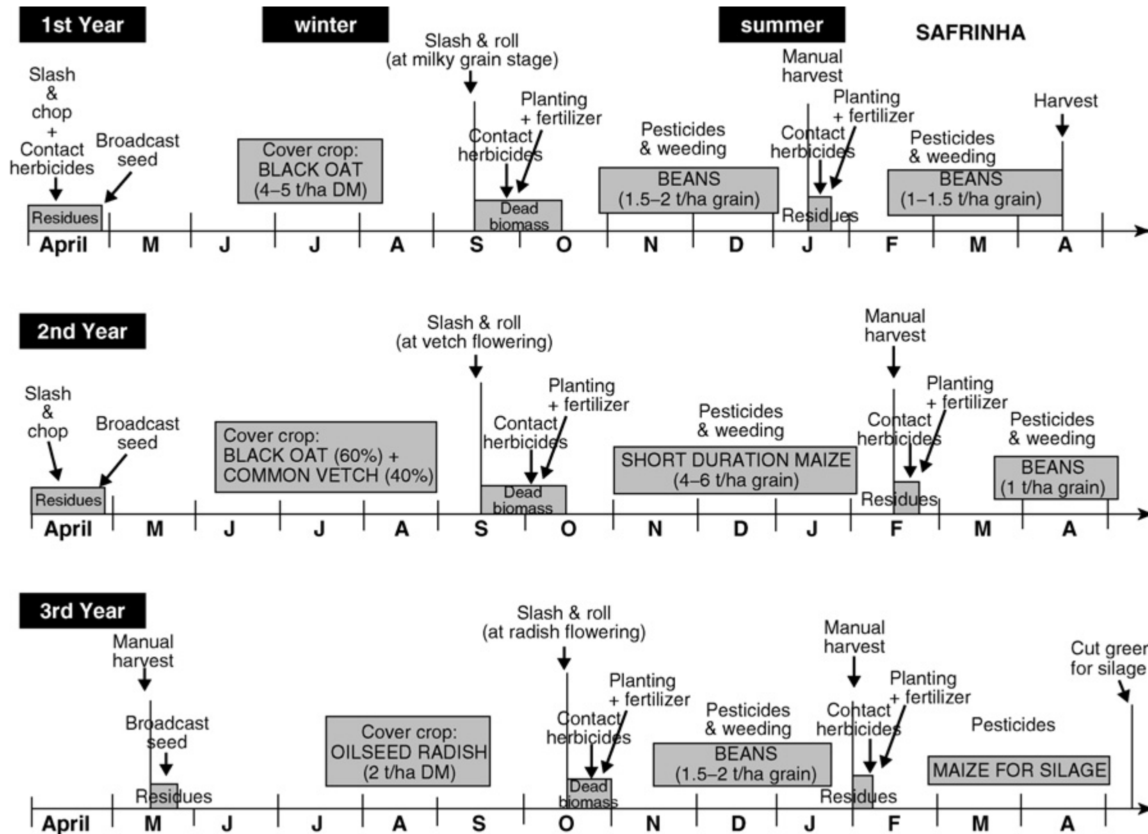
Although the primary function of cover crops is to produce biomass and soil cover during periods when available resources are too limited or too irregular for a commercial crop, most cover crops used in Brazil fulfill multiple agronomic, ecological, or economic functions in concert with those performed by the main crops (Anderson *et al.*, 2001; Calegari, 2002; Florentín *et al.*, 2001). Such general functions of cover crops broadlys include: (1) providing additional fodder, forage, food, and secondary commercial or subsistence products for livestock and humans, (2) directly adding or sparing N to/from the soil through symbiotic N_2 fixation from the atmosphere, (3) converting otherwise unused resources, such as sunlight and residual soil moisture, into additional biomass and concomitantly, upon the breakdown of their residues, increasing the build-up of SOM, (4) capturing and recycling easily leachable nutrients (nitrates, K, Ca, and Mg) that would otherwise be lost beyond the rooting zone of commercial crops, (5) ameliorating soil structure and buffering against compaction by creating additional root channels that differ from those of the main crops and by stimulating soil biological activity through, *inter alia*, the release of root exudates, (6) improving the management of acidic soils by releasing various products that can mobilize lime movement through the soil profile, decarboxylize organic anions, function in ligand exchange and add basic cations to the soil, (6) facilitating weed management by competing against or smothering weeds that would otherwise become noxious in the main crop cycle, and (7) breaking the cycle of certain pests and diseases that could otherwise build-up in continuous monocropping systems. On the other hand, integrating cover crops into existing cropping systems generally incurs extra costs in form of seed and agrochemicals (e.g., herbicides to terminate the crop before the next main crops), but also in form of extra labor and managerial skill required to establish and maintain the crop, as well as the opportunity cost of the land and equipment, while the rewards of cover crops may well take time to properly manifest themselves. Some of the major cover crops used in Brazil, together with their main advantages/functions and drawbacks, are presented in Table III, although we would like to draw

Table III
Some of the Major Cover Crops Grown in Brazil[a]

		Species	Soil and climatic requirements	Days to flowering	DM ($t\ ha^{-1}\ year^{-1}$)	Advantages and limitations
Winter	Nonlegumes	*Avena strigosa* (Schreb.)	S–C; LF-MF	120–160	2–11	AF; WC; decrease soil root diseases (*Fusarium* spp., and so on); FASM
		Lolium multiflorum (L.)	S–C	120–150	2–6	AF; WC
		Raphanus sativus ssp. oleiferus Metzg.	S–L; A–	90–110	3–9	High-nutrient recycling capacity; BP; WC; FASM
		Secale cereale (L.)	S–C; LF; A+; Wlog–; DT	100–120	4–8	BP; WC; controls some soil diseases
	Legumes	*Lathyrus sativus* (L.)	S–C; MF	100–120	2.5–4	AF; HF; mech. harvesting difficult; sensitive to aphids and diseases
		Lupinus albus (L.)	S–C; MF; Wlog–	120–140	3.5–5	AF; HF; BNF; BP; sensitive to diseases (*Fusarium* spp., and so on)
		Lupinus angustifolius (L.)	S–C; A+; Wlog–	120–140	3–6	AF; HF; BNF; BP; sensitive to diseases (*Fusarium* spp., and so on); FASM
		Lupinus luteus (L.)	S–C; LF; A+; Wlog–	130–150	3–4	Recommended for restoring depleted soils (sandy and clay)
		Pisum arvense (L.)	S–C; A–	100–130	2.5–7	AF; FEG; BNF; sensitive to aphids and some diseases
		Vicia sativa (L.)	S–C; HF; A–; Wlog–	120–150	3–5	AF; BNF
		Vicia villosa Roth.	S–C; LF; A+; WL–	140–180	3–5	AF; BNF; WC
Summer	Nonlegumes	*Brachiaria* spp.	S–C; A+	n.a.	>4	AF; BP; high biomass; SOM
		Helianthus annuus (L.)	S–C; A+; LF; DT	70–120	4–8	FEG, high nutrient recycling; WC
		Pannicum maximum (L.)	S–C; WD; DT; A+; Wlog–	n.a.	>20	FEG; AF; BP; SOM
		Paspalum notatum Flugge	S; DT; CT	n.a.	3–8	AF; SOM

	Pennisetum americanum (Schum.)	S; A+; LF; DT	90–120	3.5–21	AF; BP; SOM; WC; FASM
	Setaria italica (L.)	S–C; WD; MF; DT	45–60	2.5–8.5	AF; FEG; FASM; high-seed production
	Sorghum bicolor (L.) Moench	S–C; WD; MF; DT	60–110	3.5–18.5	AF; BP; SOM
Legumes	*Cajanus cajan* (L.) (dwarf variety)	S – L; LF; Wlog–	70–85	2–6.5	AF; NC; high-seed production
	Cajanus cajan (L.) Millsp.	S–C; LF; Wlog–	140–180	3–7.5	AF; BP; BNF + nutrient recycling, NC
	Calopogonium mucunoides Desv.	L–C	n.a.	4–10	WC; GC
	Canavalia ensiformis (L.) DC.	S–C; LF; DT	100–120	5–6	WC (allelopathic effects against *Cyperus* spp. and *Cynodon dactylon*)
	Crotalaria juncea (L.)	S–C; MF	110–140	3–8.5	BNF; WC; NC; efficient in nutrient cycling
	Dolichos lablab (L.)	S–C; LF; A+; DT; WD	75–150	4–13	AF; HF
	Macroptilium atropurpureum (DC.) Urb.	S–C; WD; A+; MF; DT	n.a.	3–6.5	AF; SOM; WC
	Mucuna pruriens (L.) DC.	S–C; LF	130–150	2–5	FEG; GC; BNF; NC
	M. pruriens (L.) DC. (dwarf varieties)	S–C; LF	80–100	2–4	NC; FASM; rain during harvesting period can damage the seeds
	Pueraria phaseloides (L.)	L; WD; Wlog–; DT	n.a.	3.5–8	AF; GC
	Stylosanthes spp.	S–C; A+, LF; DT	n.a.	n.a	AF; BP; SOM
	Vigna radiata (L.)	S–C; DT; WL–	60–80	3.5–6.5	AF; HF; high seed production
	Vigna unguiculata (L.)	S–C; L/MF; A+; WL–	70–110	2.5–5.7	AF; HF

[a] n.a., Data not available; S, light-textured (sandy) soil; L, medium-textured (loamy) soil; C, heavy-textured (clayey) soil; L/M/H, low/medium/high fertility; WD, well-drained soil; Wlog–/+, intolerant/tolerant of waterlogging; A–/+, intolerant/tolerant of soil acidity; DT, drought tolerant; AF, animal forage; HF, human food; BNF, high-N fixation; GC, produces good cover; WC, weed suppression; BP, biological plowing; SOM, good SOM builder; FASM, facilitates acid soil management; FEG, fast early growth; NC, nematode control.


1st Year
winter
summer
SAFRINHA
Slash & chop + Contact herbicides
Broadcast seed
Residues
Cover crop: BLACK OAT (4–5 t/ha DM)
Slash & roll (at milky grain stage)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
BEANS (1.5–2 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides & weeding
BEANS (1–1.5 t/ha grain)
Harvest
April M J J A S O N D J F M A
2nd Year
Slash & chop
Broadcast seed
Residues
Cover crop: BLACK OAT (60%) + COMMON VETCH (40%)
Slash & roll (at vetch flowering)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
SHORT DURATION MAIZE (4–6 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides & weeding
BEANS (1 t/ha grain)
April M J J A S O N D J F M A
3rd Year
Manual harvest
Broadcast seed
Residues
Cover crop: OILSEED RADISH (2 t/ha DM)
Slash & roll (at radish flowering)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
BEANS (1.5–2 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides
MAIZE FOR SILAGE
Cut green for silage
April M J J A S O N D J F M A

attention to the fact that cover crops are commonly also grown in mixtures rather than alone by Brazilian farmers. The function of certain cover crops in terms of building SOM, enhancing nutrient management, alleviating soil compaction, and facilitating soil acidity and weed management are elaborated in the relevant Section III.C–H.

1. Cover Crops in Subtropical Southern Brazil

As there is generally sufficient year-round moisture in most parts of Southern Brazil, temperature is the main limiting factor to crop production, frosts being frequent between late April and early September (Grodzki, 1990), making the summer the most important growing season. In general, however, the Southern Brazilian climate allows up to three crops a year, and formulaic Southern Brazilian zero-till systems comprise planting a commercial summer crop of maize, soybean, common bean, tobacco, onions, and so on, into the mulch of a winter cover crop that has previously been killed with either a knife-roller or herbicides or both. A second, shorter-duration crop or summer cover crop (referred to as "safrinha" crop) is then immediately planted into the residues of the first commercial crop in order to take advantage of the warm temperatures at the end of summer (Ribeiro *et al.*, 2005), and a winter cover crop is subsequently planted into the residues of the safrinha crop. Such a cropping sequence over 3 years for a maize/bean system in Southern Brazil is shown in Fig. 2, while Darolt (1998b) and Ribeiro *et al.* (2000) further detail different possible crop rotations suited for zero-till systems in Southern Brazil involving tobacco, dairy cattle, and soybeans, sorghum (S*orghum bicolor* L. Moench), and beans or onions as the main commercial components, and using mixtures of common cover crops such as black oat (*Avena strigosa* Shreb) and hairy vetch (*Vicia villosa* Roth), ryegrass (*Lolium* spp.), oilseed radish (*Raphanus sativus* var. Oleiferus Metzg.), corn spurry (*Spergula arvensis* L.), and mucuna (*Mucuna* spp.) as winter or safrinha cover crops.

Results obtained with winter cover crops in Southern Brazil indicate that significant yield increases can be attained if the proper cover crop is included in crop rotations (Bairrão *et al.*, 1988; Calegari, 1995, 2000, 2002; Calegari

Figure 2 Schematic representation of a model zero-till maize–bean rotational system for Southern Brazil. Safrinha refers to the short growing season following summer which Southern Brazilian farmers commonly use in order to utilize residual summer warmth before planting winter crops or cover crops. "Slash & chop" implies cutting down and shredding residues after harvest, while "slash & roll" implies slashing and laying flat an unharvested cover crop (e.g., using an animal-drawn knife-roller). "DM" refers to the amount of dry matter that can be harvested from the system as food, fodder, or fuel rather than the amount of residues remaining on the field. Information based on Darolt (1998b).

and Alexander, 1998; Calegari *et al.*, 1993, 1998a; Medeiros *et al.*, 1989). Although over a hundred different species and varieties of cover crop were screened tested and trialed throughout Southern Brazil in the 1980s (Derpsch, 2003), and many different cover crops are being used by both large and small-scale farmers in Southern Brazil (Calegari, 1998b), black oats, vetches (both *V. villosa* and *V. sativa* L.) oilseed radish, ryegrass, rye (*Secale cereale* L.), and white or blue lupines (*Lupinus albus* L. and *L. angustifolius* L.), grown alone or in mixtures, have emerged as the most common winter cover crop species (Calegari, 2002; Schomberg *et al.*, 2006). Prior to 1977, black oat, for example, was planted on a very small scale, but with the diffusion of zero-till systems, is now grown on over 3 million hectares in Paraná and Rio Grande do Sul alone (Steiner *et al.*, 2001). Data from participatory assessment of smallholder farmers' preferences regarding cover crop species in a region of Paraná indicated that farmers choice was based on criteria such as biomass production, resistance to decomposition, speed of soil cover, ease of planting the subsequent crop with animal-drawn planters, and weed suppression (Ribeiro *et al.*, 2005).

However, although the above-presented combinations of multiyear winter cover crops and summer crop rotations represent an "ideal" model for approaching permanent soil cover, soil fertility build-up, and productive farming in Southern Brazilian zero-till systems, and although it is possible to find many farmers resorting to such cropping systems on large tracts of their land, Ribeiro *et al.* (2005) argue that this does not necessarily represent the reality on the ground for the majority of resource-poor smallholder farmers. The results of a survey of 60 smallholder zero-till farmers conducted in 2004 in the Irati region of Paraná, for example, indicate that about 70% actually grew winter cover crops on any of their plots, and that, despite of the efforts of researchers and extension worker promoting the diversification of the cover crop species, few of the surveyed farmers grew anything else than black oat and ryegrass, mainly due to the better market availability and lower price of the seeds of these species compared to others, exacerbated by the fact that very few farmers produced their own seeds. Among the farmers who did grow a winter cover, most held dairy cattle, which explains the dominance of black oat and ryegrass, both species suited for animal forage. Calegari (2002) notes that a soil cover option employed by smallholder farmers in Paraná who do not plant a specific cover crop is the use of spontaneous vegetation as cover, which in Paraná is predominantly composed of alexandergrass (*Brachiaria plantaginea*). Alexandergrass which develops late in the maize season and hence does not complete with maize during its critical growth period can be killed with herbicides before the planting of the subsequent crop, thereby producing an important mulch cover (4–7 t of dry matter) into which beans, maize, cotton, or soybeans, for example, can be planted (Calegari, 2002). Alternatively, Calegari (2002)

also describes how mixtures of mucuna, planted at maize flowering, and spontaneously emerging alexandergrass can be used as a cover before both species are killed by winter frosts or by "knife-rolling" prior to the planting of tobacco.

Also, rather than rotate crops on a given plot as the ideal model system prescribes, a large proportion of farmers surveyed in Ribeiro *et al.* (2005)'s report chose to repeat the same crops over two or three of the annual cropping seasons, attempting to maximize profit rather than sustainability in the lack of any external subsidies. Palmans and van Houdt (1998) observed similar trends. Evaluating all cropping systems in the Jahu Microcatchment, northern Paraná, they found great variability in zero-till adoption levels, some farmers practicing zero-till without any crop rotations at all, others only rotating either cover or cash crops but not both, and only a small minority of farmers at the microwatershed level combining both zero-till with full rotation of cash and cover crops.

2. Cover Crop Systems in the Tropical Cerrado Region

As much of the cerrado is agricultural frontier land, and land prices are considerably lower than in Southern Brazil, most farms are consequently large (>100 ha) and mechanized. As the seasonality of rainfall in the cerrado region does not allow continuous cropping without irrigation, it is common for farmers to establish fast-growing, drought-tolerant cover crops immediately after harvest of the main crop, thereby allowing the cover crop to produce enough biomass on residual soil moisture stored under the mulch layer. The most common cover crop to be used in this way in the cerrado is millet (*P. americanum* L.), but other drought-tolerant cereals or pasture and forage species are also frequently used. Séguy *et al.* (1996) describe systems where farmers plant millet at the beginning of the rainy season rather than at the end, desiccating the millet with glyphosate 45–80 days later and planting soybeans into the millet residues. The advantage of this system compared to planting soybean first is that the millet grows much more rapidly than soybean, its roots extending at a rate of around 3 cm a day to a depth of about 1.5–2.4 m. This allows the millet to function as a pump for nutrients in deep soil strata, thereby utilizing more mobile nutrient, such as nitrates, that would otherwise be lost with the mineralization and leaching after soil wetting and drying cycles at the break of the season (Birch, 1958), but also means that more biomass and a different rooting pattern are added to the soil. Alternatively, Séguy *et al.* (2003) detail continuous zero-till systems with sequences of cover crops that remain throughout the 3- to 5-month dry season of the cerrado region, regrowing very rapidly after the first rains of the following rainy season or after sporadic dry season rain and thereby

ensuring a permanent soil cover. Such systems consist of one commercial crop (soybean, rain-fed rice, maize, or common beans) grown during the rainy season and followed by a second crop of fast-growing cereals or cover crops [millet, maize, sorghum, finger millet (*Eleusine coracana* L. Gaertn.) or sunnhemp (*Crotalaria juncea* L.)] intercropped with forage species (*Brachiaria, Stylosanthes, Axonopus*, *Stenotaphrum*, and *Cajanus* spp., as well as *Pannicum maximum* var. Tanzania, *Cynodon dactylon* var. Tifton, various varieties of *Paspalum notatum* and *Pennisetum clandestinum* and the legumes *Calopogonium mucunoides*, *Arachis pintoi*, *A. repens*, *Lotus uliginosus*, *L. corniculatus*, *Trifolium semipilosum*, *Tephrosia pedicellata*, *Stizolobium aterrinum*, and *Pueria phaseoloide*, grown alone or in mixtures) at the end of the rainy season, the latter enduring throughout the dry season after the cereal has been harvested (Scopel *et al.*, 2004; Séguy *et al.*, 1996). The forage species/pasture can then be knocked back with split rates of glyphosate and later controlled with reduced rates of selective herbicides before the planting and throughout the cycle of the next commercial crop, thereby giving the latter a competitive edge but maintaining a continuous undergrowth or "carpet" of forage species. Alternatively, the forage species can be completely terminated with full rates of glyphosate before the seeding of the commercial crop, as at this stage it has already produced sufficient mulch. Such combinations of cereals and forage species planted at the end of the rainy season allow receding soil moisture, as well as sunlight to be used efficiently during the dry season, while concomitantly producing large amounts of biomass which can be either grazed or used as green manure. Séguy *et al.* (2001) observed that under irrigation or in wetter areas (>1500 mm rainfall per year), total above and below ground annual dry matter production increased from an average of 4–8 t ha^{-1} in systems with a single annual commercial crop to an average of around 30 t ha^{-1} in the most efficient zero-till systems using, for example, *Brachiaria* species (*B. mutica*, *B. decumbens*, *B. arrecta*, *B. brizantha*, or *B. humidícola*). Some farmers in the cerrado with large livestock herds and sufficient land at their disposal leave part of their land under pasture for 3–4 years, before recommencing a 3- to 4-year cycle of zero-till grain cultivation, as this minimizes the reestablishment costs of the pasture and the need for selective herbicides, while allowing effective SOM build-up (Séguy *et al.*, 1996).

C. Soil Organic Matter Build-Up

In soils rich in high-activity clays, the effect of a loss of SOM on soil aggregation, cation exchange, and water-holding capacity may not be very detrimental to overall soil fertility. However, in areas where soil mineralogy is dominated by low-activity clays and sesquioxide material, the soil's

fertility and integrity is much more SOM dependent. In some tropical Brazilian soils, 70–95% of cation exchange capacity (CEC) is founded in SOM (Bayer and Mielniczuk, 1999). In such soils, SOM maintenance or build-up is crucial to ensuring good crop productivity, and is often postulated as the single most important element of the soil restoration process associated with Brazilian zero-till regimes. In principle, both decreased erosive losses of SOM-rich topsoil (Lal, 2002; Rasmussen and Collins, 1991) and slower SOM mineralization rates in zero-till soil compared to plowed soil suggest that zero-till may provide more favorable conditions for SOM build-up than conventional tillage. Not turning the soil, for example, means that: (1) less soil macroaggregates are disrupted, consequently leading to the increased formation of stable microaggragates that occlude and protect particulate organic matter (POM) from microbial attack (Amado *et al.*, 2006; Feller and Beare, 1997; Lal *et al.*, 1999; Six *et al.*, 1998, 1999, 2000), that (2) there is less stimulation of short-term microbial activity and concomitant release of CO_2 in response to enhanced soil aeration (Bayer *et al.*, 2000a,b; Bernoux *et al.*, 2006; Kladivko, 2001), and that (3) there is less mixing of residues deeper into the soil where conditions for decomposition are often more favorable than on the soil surface (Blevins and Frye, 1993; Karlen and Cambardella, 1996). In this context, Mielniczuk (2003) estimated the rate of SOM mineralization under conventional tillage regimes in Southern Brazil to be on average 5–6% per year compared to an average of about 3% per year in zero-till soils.

Although the actual amount of SOM storage potential in a given soil is in turn largely determined by climate and the capability of soils to stabilize and protect SOM, this itself generally being largely determined by soil texture, soil mineral surface area, and soil mineralogy, with soil parameters such as water-holding capacity, pH, and porosity acting as rate modifiers (Baldock and Skjemstad, 2000; Six *et al.*, 2002b), the large majority of Brazilian literature does indeed suggest that SOM accumulation in zero-till soils above that of plowed soils occurs, and that this is the case over a range of soil textures, from sandy loams (Amado *et al.*, 1999, 2000, 2001, 2002, 2006; Bayer *et al.*, 2000a,b, 2002) to heavy clay (>60% clay) soils (Amado *et al.*, 2006; De Maria *et al.*, 1999; Perrin, 2003), both in Southern Brazil (Muzilli, 1983; Sá *et al.*, 2001a,b; Zotarelli *et al.*, 2003), as well as in the cerrado region (Corazza *et al.*, 1999; Freitas *et al.*, 1999; Resck *et al.*, 1991, 2000; Scopel *et al.*, 2003). Bernoux *et al.* (2006) recently reviewed some 25 published and unpublished data sets on the rate of C (SOM ~58% C) accumulation in Brazilian zero-till soils and observed that reported C accumulation rates in excess of those found in comparable plowed soils vary from around 0.4–1.7 t C ha^{-1} $year^{-1}$ for the 0- to 40-cm soil layer in the cerrado region and between −0.5 and 0.9 t C ha^{-1} $year^{-1}$ in Southern Brazil. They further noted that average rates of C storage amounted to about 0.6–0.7 t of C ha^{-1} $year^{-1}$

in all reported regions of Brazil when the soil surface layer was considered (0–20 cm), although these values combine different soil and crop types, and the actual site-to-site/experiment-to-experiment variation was high. We found over 40 published articles relating to SOM dynamics in Brazilian zero-till regimes (with very few exceptions all from experimental stations or trial plots rather than farmers' fields), but reviewing them in more detail reveals a varied picture, which is compounded by the fact that relevant reports originate from various climates and soils with diverse tillage, cropping and fertility management histories, as well as often being sampled to different depths and based on analytical and calculation methods of varying accuracy. Freitas *et al.* (1999), for example, observed increases in SOM in coarse particle-size fractions (200–2000 μm) down to 20-cm depth compared to similarly cropped but plowed land in a clayey cerrado Oxisol already after only 4 years of zero-till, while other work reported a decrease in SOM compared to plowed soil down to a depth of 10 cm after 3 years in a Oxisol in Toledo (Riezebos and Loerts, 1998), to a depth of 20 cm after 11 years of zero-till in an Oxisol in Passo Fundo (Machado and Silva, 2001), to a depth of 40 cm after 10 or 22 years of zero-till in either a well drained, Typic Hapludox Oxisol in Tibagi (Sá *et al.*, 2001a) or an Oxisol in Londrina (Machado and Silva, 2001), respectively, and Sisti *et al.* (2004) and Castro Filho *et al.* (2002) found no significant increase in SOM down to 30-cm depth in a clayey Typic Hapludox Oxisol after 13 years of zero-till in Passo Fundo or down to 40-cm depth even after 21 years of zero-till in a Typic Haplorthox Oxisol in Londrina, respectively.

Sampling depth is an important issue in terms of SOM accumulation studies in Brazil, and results are strongly influenced by the pattern of SOM storage. In the absence of soil inversion and mixing, zero-till soils have highly stratified SOM stocks, SOM being most concentrated near the surface and gradually decreasing with depth (Machado and Silva, 2001; Sá *et al.*, 2001a,b). Additionally, and importantly in this context it is essential to note that direct comparisons in absolute SOM storage between plowed and zero-till soils are inappropriate if soil depths less than 20 cm are considered, as conventional soil tillage homogenizes SOM down to 20 cm (Bernoux *et al.*, 2006; Reicosky *et al.*, 1995). Deeper samples, however, also show different trends. Studies performed in the cerrado region by Centurion *et al.* (1985) and Corazza *et al.* (1999) showed that while soil C stocks under zero-till were higher than under plowed soils in the surface 20 or 30 cm, extending sampling depth to 100 cm evened out global differences in SOM between tillage systems due to lower C content under ZT in the 30- to 100-cm depth interval. Sisti *et al.* (2004), on the other hand, found much larger differences in total SOM between zero-till and plowed soil if soils were sampled down to a depth of 100 cm, the 30- to 100-cm depth interval containing between 50% and 70% of the extra C in zero-till compared to tilled soil. This, they

reasoned, could possibly be explained by the greater root density at depth under zero-till compared to the plowed soil in their study, while the acidic subsoil in the studies by Centurion *et al.* (1985) and Corazza *et al.* (1999) in the cerrado region may have inhibited much rooting at depth. We found no other Brazilian literature that reports SOM storage at depths greater than 40 cm.

Brazilian research data also indicate that the pattern and quality of SOM in zero-till soils differs to that of plowed soils. Various research has also found that the relative amount of free labile or more recent (e.g., POM) rather than humified and occluded SOM fractions is higher in zero-till soils compared to plowed soils, which is in turn has important ramifications for soil structure, nutrient cycling and as a source of energy for soil microbial biomass. Using a particle-size fractionation technique combined with electron spin resonance, Bayer *et al.* (2000b), for example, observed that soil organic C (SOC) associated with sand and silt fractions in zero-till soils was less humified and therefore younger than that associated with finer fractions, while Sá *et al.* (2001a) reported that although they also found higher SOC concentrations in the finer particle-size fractions (<20 μm) under zero-till compared to conventional tillage, the percentage of SOC derived from crop residues, as assessed by ^{13}C natural abundance, was generally greater in the coarse (>20 μm) fractions than in the finer ones. Similarly, Amado *et al.* (2006), investigating SOM storage in four long-term trials in a range of light (<9% clay) to heavy (>70% clay) soils in Southern Brazil, noted that free light fraction SOM was on average 3.5 times higher under zero-till than in tilled soil, stipulating that this was probably a consequence of lower soil temperatures and residue-soil contact in zero-till soils compared to plowed soils. They therefore conclude that physical protection of SOM was important in zero-till, especially in sandy soils, but that in contrast to neighboring soils under native vegetation, soil texture played a less important role in short-term SOM stabilization.

Finally, and most importantly in terms of actually managing SOM buildup, the increase in plant biomass per unit of land and time through fast-growing cover crops typical for Brazilian zero-till systems means that more fresh organic matter is added to soils than under traditional double-cropping plow regimes. Although physicochemical characteristics inherent to different soil may partially limit increase in SOM with increased organic inputs, various studies suggest that SOM responds linearly to increasing rates of residue addition over a variety of soils and climates (Bayer, 1996; Black, 1973; Burle *et al.*, 1997; Rasmussen and Collins, 1991; Testa *et al.*, 1992; Teixeira *et al.*, 1994). Burle *et al.* (1997), for example, obtained a close relationship between SOC in the 0- to 17.5-cm soil layer and residue quantity added by 10 different zero-till cropping systems. Results obtained by Bayer (1996) stipulated that after 9 years of zero-till with high-residue addition

(14 t of dry matter per ha per year), SOC content increased by 11 t ha^{-1} in the top 17.5 cm of soil compared to conventional cropping systems that only yielded additions of 6.5 t of residues ha^{-1} year^{-1}. In Southern and tropical Brazil, with average annual temperatures close to or above 20°C and concomitantly high-decomposition rates, it is therefore probably necessary to annually add between 8 and 10 t of residue dry mass ha^{-1} year^{-1} in order to maintain the SOM stocks under zero-till, which, as Mielniczuk (2003) postulates is only really feasible if both suitable high-biomass cover crops and main crops are resorted to. Especially fodder grasses, as used as dry season cover crops in the cerrado (Section III.B.2), but also cereal cover crops, such as millet, sorghum, and black oat, or crucifers, such as oilseed radish and legumes such as vetches and lupines (Calegari, 1998c), can produce high amounts of biomass (Table III), and in combination with high-residue producing main crops, such as maize rather than soybean or wheat, can help boost SOM stocks. Importantly also in this context, it is essential to consider below-ground biomass of crops and cover crops, especially as the C added in roots can be close to double that of shoots (Mielniczuk, 2003) and, as discussed earlier, Sisti *et al.* (2004) found increased roots under zero-till compared to plowed soils well below plowing depth.

De Maria *et al.* (1999) compared SOM stocks after 9 years of either maize or soybean in summer and oat in winter both under zero- and conventional tillage. Despite the fact that maize produced much larger biomass quantities, these did not increase SOM under either tillage type, and SOM actually decreased over the study period in all treatments. As the net N balance (fertilizer N – grain N export) was only about 20 kg of N per hectare, the lack of SOM accumulation under either tillage treatments may be related to the lack of sufficient external N input to the system. Sisti *et al.* (2004) and Amado *et al.* (2006) further studied the role of N additions in SOM build-up under zero-till in Brazil, and both found that where rotations with N_2-fixing legumes were included, much more SOM was accumulated, hence highlighting the fact that for there to be an accumulation of SOM there must be not only a C input from crop residues, but a net external input of N. Sisti *et al.* (2004) observed that where hairy vetch was planted as a winter cover crop in rotations that included common oat and wheat in winter and maize or soybean in summer, soil C stocks were increased by approximately 10 t ha^{-1} down to a depth of 100 cm after 13 years of zero-till, soil C being 17 t higher in this soil layer than in comparable plowed soils. They further postulated that where net N balance was close to zero over the whole crop rotation, little SOM accumulation was to be expected. Amado *et al.* (2006) reported that pigeonpea and mucuna cover crops integrated into zero-till maize cropping systems had the highest C accumulation rates under zero-till and that intensive cropping systems, including mixes of black oat with hairy vetch in winter and maize with cowpea in summer, as well as rotations of

oilseed radish and ryegrass, among other crops, effectively increased zero-till C accumulation rates compared to more conventional double-crop systems used by many farmers.

In summary, a large body of Brazilian work corroborates the fact that SOM accumulates under zero-till in excess of that under plowed land, and that farmers can in theory influence SOM build-up through astute crop rotations and appropriate liming and fertilization regimes. The amount and rate of SOM build-up is, however, less clear. This complexity of data on Brazilian SOM accumulation make it hard to draw any firm conclusions about a possible timeframe for which SOM levels significantly increase. However, Six *et al.* (2002a), reviewing literature on SOM dynamics in tropical and temperate zero-till soils around the world, remarked that there commonly is a relative increase in SOM in the upper 40 cm of zero-till soil after 6–8 years when compared to tilled systems under similar cropping regimes, and this pattern could potentially hold true for a large amount of the Brazilian data.

D. Nutrient Management

Possibly one of the most important immediate nutrient effects of zero-till is the potential of the residue cover to restrict N availability. Residues with a high C to N ratio, such as black oat, wheat, maize, sorghum, and ryegrass, commonly induce N immobilization in soil surface strata during decomposition, although the magnitude of this effect is dependent on residue quantity and quality, as well as the mineral status of the soil. Sá (1999) suggests that the immobilization process is most intense during the first years of zero-till, but after 5 or more years, gradually diminishes due to the increased surface concentration of SOM acting as an N source and thereby effectively counteracting N limitations induced by residues. Especially as zero-till increases the POM stock, which is strongly correlated to potentially mineralizable N, soil N availability under long-term zero-till is suggested to increase over time when compared to conventional tillage (Sá *et al.*, 2001a,b). During the first few years of zero-till, however, cereal response to N fertilization is high, and generally N-fertilization is recommendable or necessary (Calegari, 2002), although care should be taken to distance fertilizer deposition as far as possible from the mulch in order to avoid fertilizer immobilization (Wiethölter, 2002).

An option of adding N to the system and alleviating immobilization-induced N constraints under zero-till is by rotating legumes with non-legumes, as well as mixing legume swards with nonlegume stands. Residues with a low C to N ratio as common vetch, lupine species, soybean, oilseed radish, mucuna, jackbean (*Canavalia ensiformis* L. DC.), or pigeonpea can

increase N availability. Much work has been conducted on the nutrient content and residual effects of common cover crops in Southern Brazil, Paraguay, and Uruguay (Amado *et al.*, 1990b; Calegari, 1989, 1990, 1995; Calegari *et al.*, 1993; Derpsch and Calegari, 1992; Derpsch and Florentin, 1992; Igue, 1984; Jucksch *et al.*, 1984; Kage, 1984; Lovadini *et al.*, 1972; Monegat, 1991). Relating to the results of trials conducted over 2 years at IAPAR in Londrina, Derpsch *et al.* (1986), for example, reported that maize fertilized with P and potassium (K) produced highest yields after preceding crops of white lupine and hairy vetch, when compared to yields after grasspea (*Lathyrus sativus* L.), cereals, and sunflower. This can be explained by the fact that appropriate legume residues can decrease maize mineral N requirement by about 60–90 kg ha^{-1} (Amado *et al.*, 2000; Calegari, 1995; Sá, 1999). Both in tropical and subtropical Brazil, legume residues left on the soil surface decompose rapidly and provide a prompt N release, sometimes so fast that it causes asynchronies with maize demand (Acosta, 2005; Giacomini, 2001; Vinther, 2004). Common vetch residue left on soil surface in Santa Maria, for example, released 60 kg of N per hectare in only 15 days (Acosta, 2005). Derpsch *et al.* (1986) also noted high-maize yields after oilseed radish in the same trials, which they explained as a consequence of the high amount of N (135 kg ha^{-1}) in the plant shoots and roots at harvesting time. Muzilli *et al.* (1983), Calegari (1985), Amado *et al.* (1990b), Derpsch and Calegari (1992), and Debarba and Amado (1997) all also reported positive effects of N supply provided by legume cover crops such as white lupine and hairy vetch in Southern Brazil, while Carvalho *et al.* (1996) noted that pigeonpea and sunnhemp fulfilled a similar function in the cerrado region. Sisti *et al.* (2001) actually found that legumes grown under zero-till symbiotically fixed a higher proportion of their N requirements compared to legumes sown to plowed soil, which is presumably a consequence of the lower rates of N mineralization and concomitant higher dependency on fixation when soils were not turned. Acosta (2005), using ^{15}N labeling, found that common vetch symbiotically fixed 50–90% of its N requirement in a zero-till trial in Santa Maria, Rio Grande do Sul. Burle *et al.* (1997) trialed mixed stands of cover crops over 10 years and found maize unfertilized with N to respond best to a preceding mixture of black oats and hairy vetch compared to nine other cover crop combinations planted prior to maize (Table IV). This is most probably a result of the maize profiting both from the beneficial effects of lasting soil cover and large C inputs generated and gradually laid down by the fast-growing oat, as well as the symbiotically fixed N from the vetch. Giacomini *et al.* (2003) also found mixtures of black oats or oilseed radish and hairy vetch to be the most efficient way of combining both physical soil protection through long-lasting residues and high-biomass production with N fixation in Southern Brazilian zero-till systems.

Table IV
Maize Yields on a Zero-Tilled Oxisol in Southern Brazil After 10 Years of One of Seven Cropping Regimes and Fertilized with Either 0 kg ha^{-1} N or 120 kg ha^{-1} N[a]

Cropping systems studied		Grain yields (t ha^{-1})	
Winter	Summer	0 kg ha^{-1} N	120 kg ha^{-1} N
Avena strigosa	Maize	2.0 a A	7.1 B
A. strigosa + *Vicia sativa*	Maize + *Vigna unguiculata*	6.6 b B	7.6 B
A. strigosa + *Trifolium subteraneum*	Maize	5.4 b B	7.0 B
Macroptilium atropurpeum (8 years)	Maize (5th and 10th year)	5.7 b A	8.3 B
Cajanus cajan	Maize + *C. cajan*	5.4 b B	7.2 B
Fallow	Maize	1.1 a A	6.5 B
Digitaria decumbens (8 years)	Maize (5th and 10th year)	1.3 a A	6.8 B

[a]Means followed by the same small letter down rows or capital letter across columns are not significantly different using the Tuckey test at $p = 0.05$ (data from Burle *et al.*, 1997).

For zero-till maize production in Southern Brazil, variations in traditional mineral N fertilization regimes have also been tested. The use of part of maize N fertilization in the black oat cover crop had a positive effect in terms of increasing black oat residue quantity and quality (lower C:N ratio), but this in turn had a fairly limited effect on N supply to the following maize crop (Amado *et al.*, 2003). Another zero-till fertilizer strategy is to use the total rate of mineral N at cover crop termination (approximately 15 days before the seeding the main crop) or at maize seeding time rather than apply N in split applications, assuming that the residue mulch will temporarily bind added N and thereby partially prevent leaching losses of N, as this eliminates the need for an additional field operation. However, in terms of maize yields, this strategy was only efficient in years with light rainfall during maize growth (Basso and Ceretta, 2000; Pöttker and Wiethölter, 2002; Sá, 1999). In years with high rainfall, the traditional strategy of applying one-third of N at seeding and the remaining two-thirds as a top dressing after 6 weeks was more efficient (Ceretta *et al.*, 2002; Pöttker and Wiethölter, 2002).

As N fertilizer is not thoroughly mixed into the soil, concerns about N volatization in zero-till are frequent (Blevins and Frye, 1993). Cabezas *et al.* (1997), for example, evaluated the efficiency of broadcasting of urea, the most common mineral fertilizer source of N in Brazil, on mulch, and found that about 80% of N was lost through volatilization. In this context, however, we would like to stress that this result was obtained under hot and dry conditions common in the cerrado, and under wet winter conditions in Southern Brazil, Wiethölter (2002) found that only about 5% of broadcast

urea-N was lost by volatilization in a wheat crop. The discrepancy between the results most likely is explained by the differences in weather conditions. A light rain after broadcast urea in zero-till can reduce the N volatilization.

As with N, P has been shown to accumulate in soil surface strata under zero-till regimes (Sá, 1999), due to the management effect of broadcasting or row applying P fertilizer rather than incorporating it, but also due to decomposition of P-containing residues on the soil surface and the slow movement of P through the soil profile. As this corresponds to soil strata that is richest in SOM under "mature" zero-till, P phytoavailability has been shown to improve, due both to lower P sorption on clay particles and iron and aluminum sesquioxides surface, as well as due to increased biological activity in this strata (Afif *et al.*, 1995; De Maria and Castro, 1993; Falleiro *et al.*, 2003; Fontes *et al.*, 1992; Lopes *et al.*, 2004; Muzilli, 1985; Reinert, 1982; Sá, 1999; Selles *et al.*, 1997; Sidiras and Pavan, 1985; Silva *et al.*, 1997). This effect is exacerbated by the fact that there is generally also a higher concentration of surface roots under zero-till compared to plowed soils (Holanda *et al.*, 1998; Stone and da Silveira, 1999). Gassen and Gassen (1996), for example, reported that after some years, demand for fertilizer P is up to 50% lower under zero-till compared to crops with the same P uptake in plowed soil. Furthermore, Sá (1999) found that organic P made up 70% of total P in the 0- to 20-cm soil strata under zero-till, consequently suggesting that organic P in zero-till could play an important role in maintenance of the P equilibrium in the soil solution as it is more mobile than inorganic P. Lopes *et al.* (2004), however, only found organic P in an Oxisol to amount to 25–35% of total P, and Oliveira *et al.* (2002) argue that, similarly to N, P in the first years of zero-till is immobilized in the organic matter that is being built up, the SOM therefore acting as a temporary P drain before the beneficial effects of SOM on P phytoavailability become evident.

Similar to N and P, but also calcium (Ca) and magnesium (Mg) (Calegari, 2002), K has a higher concentration in topsoil (0–10 cm) than in deeper soil layers under zero-till, but, due to its high-soil mobility, its stratification is not as extreme as that of P. The significant increase of CEC as a result of increased surface SOM concentrations under zero-till, especially in low activity or sandy soils, has also been shown to greatly reduce K leaching under zero-till compared to plowed soil (Bayer, 1996). Furthermore, crop rotations have proved particularly important in the maintenance of K under zero-till, with cover crops, such as millet and oilseed radish oil having a high potential to absorb and hence recycle K, hence functioning as K catch crops and thereby reducing K leaching losses. In the cerrado region, where many soils have low K, the combined use of K fertilizers and cover crops with zero-till showed an increase in soil K above that of conventional tillage (Lopes *et al.*, 2004).

E. Soil Compaction

Soil compaction is another contentious issue in Brazilian zero-till, which, if severe, can potentially both curtail infiltration rates, as well as restricting crop root development, which in turn is especially important in areas prone to periods of in-season drought and poor soil fertility. While soil compaction is a natural process, the cohesion between aggregates tending to decrease under the flux of water in soil, this process is counterbalanced in natural ecosystems by intensive biological activity throughout the soil profile. In cultivated land, on the other hand, compaction is often accentuated by the random traffic of machinery, animals, or humans (McGarry, 2003). Plowing is in turn commonly used to remedy compacted soil, at least to 20-cm depth, while in Brazilian zero-till, activating and enhancing biological activity is the key to avoiding natural or man-induced compaction, as is the case in natural ecosystems (Scopel *et al.*, 2003). In theory, bulk density may well increase over time under zero-till, but infiltration rates remain reasonable due more favorable porosity, pores being continuous and vertical, postulate McGarry (2003) and Scopel and Findeling (2001). Farmer experiences with soil compaction published in the Brazilian literature, however, are somewhat conflicting. Sá (2000) gives soil compaction and resulting yield declines, especially during dry periods, as a reason for some Southern Brazilian farmers to abandon zero-till and returning to conventional cultivation. Ribeiro *et al.* (2005), relying on data from a survey of 60 farmers in southern Paraná, elaborate on this, maintaining that farmers justify the use of chisel ploughs for soil decompaction or for breaking soil crusts, the latter occurring specially in soils with high amounts of silt. Conversely, however, Derpsch (2001) argues that compaction does not translate in reduced soybean yields, while researchers in Rio Grande do Sul further reason that soil compaction there is not big issue, despite the high sand and silt content making soils very prone to compaction, because suitable planter-rippers are able to break the shallow soil compaction induced by cows over the winter period.

In more detail in terms of experimental trials, Derpsch *et al.* (1986) found that after 7 years of zero-till, bulk density at 0- to 20-cm depth in a clayey Oxisol in Southern Brazil was greater than under conventional tillage, whereas the plowed soils had more or less pronounced "plow pans" at 20- to 30-cm depth. Furthermore, total and macropore volume was considerably lower under zero-till, while mesopore space was higher and micropore space unchanged between tillage systems. Corsini and Ferraudo (1999), on the other hand, found that although during the first 3 years of zero-till on a clayey Oxisol soil macroporosity and root development was lower under zero-till than in an adjacent tilled plot, the long-term benefits of continuous zero-till on soil macroporosity kicked in during the fourth year. After this, macroporosity

and root development values increased and matched corresponding levels of freshly plowed soils in the experimental area during the eighth year. Similarly, Machado and Silva (2001) and Oliveira *et al.* (2003) remarked that bulk density at 0- to 20-cm depth after 11 or 20 years of zero-till on an Oxisol was not greater than bulk density under conventional tillage on the same soil. At 20–30 cm, however, bulk density of the plowed soil was greater than of the zero-till soil.

Part of the relative "ecompaction" process is undoubtedly due to the effects of gradual increases of SOM on soil structure and integrity. SOM has a direct impact on soil bulk density (or inversely on the porosity), both because the particle density of organic matter is considerably lower than that of mineral soil, but also because SOM is often associated with increased aggregation and permanent pore development as a result of increased soil biological activity (Franzluebbers, 2002). Various Brazilian authors have pointed at the beneficial influence of increased surface SOM levels under zero-till on soil structural stability and aggregate size and stability (Campos *et al.*, 1995; Carpenedo and Mielniczuk, 1990; Castro Filho *et al.*, 1998; Silva *et al.*, 2000), although the degradation and the opposite process—restoration of structural stability under zero-till—have been shown to be very dependent on soil texture and are much faster in sandy soils than in clayey soils. Borges *et al.* (1997), for example, observed that zero-till on sandy (>70% sand) soil restored water aggregate stability to near 70% of original levels of undisturbed soil after 3 years, whereas Da Rós *et al.* (1996) found that in clayey soil, where SOM storage potential was much greater, similar values were only achieved after 9 years of zero-till. Castro Filho *et al.* (1998) further reported that soil aggregation had a tendency to increase when crop rotations included plant species such as maize, whose residues had high C to N ratios. Roth *et al.* (1988) concluded that even though porosity was lower in soils after 7 years of zero-till compared to tilled soil, this was offset by a higher aggregate stability under zero-till, so that in the end no significant differences in infiltrability were found between tilled and untilled soils, even when neither soils were covered by adequate amounts of residues.

Additionally to the effect on soil aggregation, the increase in SOM in surface layers under zero-till may also affect plant-available moisture levels, as SOM has a greater water-holding capacity than mineral soil (Franzluebbers, 2002), and even if roots growth is restricted, this may be compensated by the fact that roots need to explore less soil volume to get water. Another explanation for the absence of yield decreases even in soils of high bulk density is that, as put forward earlier in this section, roots and water may exploit continuous biopores and channels generated by previous plants or soil fauna (Ehlers, 1975). Using suitable crops to break through compacted soil layers and create biopores is a feasible strategy to circumvent

compaction problems. Kemper and Derpsch (1981) argue that crop rotations involving deep-rooted cover crops, such as hairy vetch, sunflower, castor bean (*Ricinus communis*), pigeonpea, or oilseed radish, may promote biological loosening of compact soils. Machado and Silva (2001) showed that if hairy vetch and maize were included in zero-till rotations of soybean and wheat, soil bulk density actually tended to be lower than in plots only cultivated with soybean and wheat. Especially a bulbless variety of oilseed radish is often reported as an outstanding example of biological plowing in Brazil, while Séguy *et al.* (2003) maintain that plant species, such as *Brachiaria*, *Eleusine*, or *Cynodon* species, are very efficient in restoring the soil structure both thanks the abundance of roots they develop in the first 0–40 cm of soil, as well as their overall strong root systems.

F. Soil Acidity and Aluminum Toxicity

The control of soil acidity is often viewed as one of the most controversial aspects of effective zero-till. Due to the absence of soil inversion under zero-till systems, applied sources of lime are not physically mixed into deeper soil strata, and different approaches are required in order to tackle soil acidity problems. The most conventional approach is to rectify soil acidity before commencing zero-till, and Derpsch (2001) and Aghinoni (1989) recommend applying lime the year before entering into zero-till, thereby making use of the opportunity to incorporate lime. In general, if crop residues are thereafter returned to the soil, acidification should not present a problem due to the decarboxylization of organic anions, ligand exchange, and the addition or retention of basic cations (Miyazwa *et al.*, 1993; Yan *et al.*, 1996). Research by Kretzschmar *et al.* (1991), for example, showed that millet straw left on fields increased pH from 4.5 to 5.7 over 6 years. Long-term tillage and crop rotation experiments on acidic soils in Brazil have indicated that zero-till may increase pH, KCl-exchangeable Ca and Mg, and Mehlich-1 P, and decreased KCl-exchangeable Al (Calegari, 1995; Calegari and Pavan, 1995; Sidiras and Pavan, 1985) compared to conventional tillage (Machado and Gerzabek, 1993; Muzilli, 1983; Sidiras and Pavan, 1985).

Another approach is to broadcast lime or dolomite on the soil surface and allow it time to leach (Caíres *et al.*, 1996; Lopes *et al.*, 2004). Work by Sá (1993) indicated that surface application of lime after 270 days was superior to its incorporation to 20-cm depth with zero-till on distrophic red-yellow and dark red Oxisols in Paraná, while Lopes *et al.* (2004) agree that when the level of soil P is satisfactory, it is possible to achieve highly productive cultures in zero-till soils by applying calcareous material to the soil surface without incorporation, the quantity of material needed for this being lower than when the material is incorporated into the soil, although the maximum

effect on soil acidity is limited to the 0- to 10-cm soil layer. The actual mobility of lime through the soil profile to date still appears to be rather uncertain. Results of both laboratory and field studies using Brazilian soils indicate little or no downward movement beyond the point of placement, limiting the effectiveness of the surface-applied lime to the top 5–10 cm (Gonzalez-Erico *et al.*, 1979; Miyazawa *et al.*, 2002; Pavan *et al.*, 1984; Ritchey *et al.*, 1980), while other work reports fairly rapid movement of lime through the soil profile (Chaves *et al.*, 1984; Morelli *et al.*, 1992; Oliveira and Pavan, 1996; Wright *et al.*, 1985). In a field experiment over 5 years on a clayey Oxisol in Paraná, Oliveira and Pavan (1996) surface applied various rates of lime and found that one quarter of the lime (dolomite) rates required to achieve 60% base saturation applied annually over 4 years increased soil pH significantly down to a depth of 40 cm over the experimental period, and that this resulted in improved soybean yields similar to those achieved when dolomite was incorporated to a depth of 20 cm, as compared to no liming. They argued that the apparent contradictions between mobility rates in other research could be an artifact of the differing soil management and cropping conditions, allowing for more or less complete reaction of the lime at the point of placement. In the studies of Gonzalez-Erico *et al.* (1979), Ritchey *et al.* (1980), Pavan *et al.* (1984) and Miyazawa *et al.* (2002), surface soil pH remained low and lime reacted completely at the point of placement with little pH change being evident deeper in the soil. Oliveira and Pavan (1996) also postulate that dolomite may possibly have followed old weed and crop root channels in the undisturbed soil to react with acidity at greater depths, as well as being transported by water or organic residue decomposition products through the well-drained, porous, and highly structured zero-till Oxisol they conducted field experiments on, as opposed to disturbed soils which were used in other experiments. Machado and Silva (2001) further maintain that channels made by macroarthropods and annelids could also influence lime movement, while Kaminski *et al.* (2000) proposed that crops grown on zero-till land suffered less from aluminum toxicity as their roots often followed the channels produced by insects or the decay of previous roots in the soil profile, such channels having lower levels of aluminum, higher levels of exchangeable Ca and Mg, raised available P and K, more organic matter, and higher pH than the adjacent soil. Some Brazilian zero-till farmers corroborate this view by claiming that after a number of years of zero-till, the soil has both a good enough structure to allow surface-applied lime to percolate into deeper layers even without plowing and that their crops do not suffer from the usual effects of low pH/aluminum toxicity.

The downward movement of Ca and Mg from the dolomite to deeper layers as a result of the formation of hydrosoluble organic compounds

present in plant residues has recently gained more attention within the same group of researchers from IAPAR (Cassiolato *et al.*, 1998; Franchini *et al.*, 1999a,b, 2001; Meda *et al.*, 2001; Merten and Fernandes, 1998; Miyazawa *et al.*, 2002; Ziglio *et al.*, 1999). Low-molecular weight organic acids, such as malate and citrate, produced during decomposition of blue lupine and oilseed radish on an Oxisol were able to form stable Al complexes (Franchini *et al.*, 1998, cited in Machado and Silva, 2001). Miyazawa *et al.* (2002) used leaching columns of disturbed acid soil in a greenhouse experiments to evaluate the effect of plant residues on the mobility of surface-applied calcite lime through the soil profile. They applied black oats, rye, mucuna, leucaena (*Leucaena leucocephala*), and wheat straw at a rate of 40 t of dry matter per hectare to the soil surface in combination with 3 t ha^{-1} of lime and an irrigation program equivalent to 1500-mm rainfall per year, and found that while the effect of lime without plant residues was limited to the upper 10-cm profile, lime combined with plant residues increased pH deeper in the soil, as well as generally increasing Ca and decreasing free Al concentrations in the soil profile compared to an untreated control. The efficiency of plant residues on lime mobility differed between species, black oats inducing the largest effect, followed by rye, mucuna, and leucaena, respectively, with the wheat residue treatment not differing from the sole lime application. Miyazawa *et al.* (2002) explained the results through the presence of carboxyl and phenolic compounds in the decomposition products of the residues, which acted as ligands forming uncharged or negatively charged metal–organic complexes with Ca, thereby facilitating the movement and leaching of Ca through the negatively charged clay soils. The difference in amounts of these carboxyl and phenolic compounds in the decomposition products of the residues of different species would subsequently explain species differences, with the minimal effect of wheat residues on lime mobility in soil due to their low concentrations of organic acids. Putting Miyazawa *et al.* (2002) results into a farmers' field context, 40 t of residues probably more than most farmers would produce. However, combined with the potential of lime movement through the porous structure of an undisturbed soil, as well as the movement of the lime in the decomposition products, this indicates that farmers potentially can control subsoil acidity with surface-applied lime and appropriate cover crops. Machado and Silva (2001), however, raise concerns that in systems where fertilizers are applied, surface liming may also reduce the efficiency of surface applied N (by volatilizing NH_3) and P (by complexing P with Ca^{2+}) and furthermore, that promising cover crop species, such as sunnhemp and pigeonpea, may not produce organic acids capable of forming stable Al complexes. More research in this respect is, therefore, potentially still necessary.

G. Weed Management

One of the primary reasons for tillage is to control weeds. In the absence of soil inversion to bury and/or induce premature germination of weed seeds, or sever the roots and storage organs of annual and perennial weed species, and instead relying to a greater extent on herbicides, crop rotations, and hand weeding, the weed spectra in zero-till systems commonly differ from those under conventional tillage practices. Furthermore, as soil characteristics, such as bulk density and cover, are changed, these can have a direct influence on weed seedling emergence (Moyer *et al.* 1994). Small seeds of alexandergrass [*Brachiaria plantaginea* (Link) A. S. Hitchc.], for example, although they generally emerge from deeper soil layers in cultivated than in uncultivated soils due to changed bulk density (Lorenzi, 1984), are commonly incapable of germinating and emerging from soil deeper than 1 cm (Roman and Dinonet, 1990), hence being favored by zero-till and having become a major weed species in Southern Brazilian zero-till systems (Derpsch, 2003). A 6-year field study to evaluate the effects of tillage systems on weed density and species composition in rotations including wheat, soybean and maize in Argentina revealed that the weed spectrum changed rapidly in zero-till plots (Tuesca *et al.*, 2001). In wheat, annual broad-leaved species showed higher populations in plowed soils in 4 out of 6 years, while grassy annuals and perennial species showed an erratic response to tillage systems. In summer crops, broad-leaved weeds were higher in plowed soil than in zero-till for the last 5 years in the wheat/soybean rotation and for the last 4 years in the maize/soybean rotation. Over time, grassy annual populations increased in the maize/soybean rotation, and wind-dispersed weed populations increased in the wheat/soybean rotation, but perennial weeds maintained inconsistent behavior in relation to tillage type in the maize/soybean rotation. Machado *et al.* (2005) observed that purple nutsedge (*Cyperus rotundus*) remained the most important species in plowed maize systems after a 4-year trial on a clayey Ultisol in the State of Minas Gerais that had originally been infested with that weed species, but that the broad-leaved weed species (*Amaranthus deflexus*, *Bidens pilosa*, *Euphorbia heterophylla*, *Galinsoga parviflora*, and *Ipomoea grandifolia*) rather than purple nutsedge became dominant in zero-till maize. Roman and Dinonet (1990) observed a decrease in annual weed populations in a long-term double cropping system on farmers' fields that involved wheat, maize, and soybeans in Southern Brazil, while there was no indication that biennial weed densities increase in zero-tillage systems. Moyer *et al.* (1994) conclude that it is difficult to predict the type of weed population that emerge in cropping sequences that include several crops, especially under different edaphic and climatic conditions and if several different herbicides for weed control are used.

Nevertheless, weed management in the absence of plowing is a contentious issue in Brazilian zero-till, as it does commonly necessitate increased reliance on herbicides. In their survey of 31 smallholder farms in Paraná using mainly animal traction for drought and where weed control in conventional systems is mostly based on plowing, Samaha *et al.* (1998) noted that herbicide expenditures in conventional smallholder systems amount to about 2% or 5% of total production costs for either maize or beans respectively, but increase to 11% and 12% in similar zero-till systems. Rego (1993), also resorting to smallholder data from Paraná, corroborates this trend by stating that zero-till on average induces an increase of 17% in the use of herbicides when compared with conventional tillage in general, while conversely Silva (2002) argues that over time, successful zero-till systems in the cerrado tend to reduce the amounts of herbicides that are necessary (due mainly to decreased seed banks and weed-smothering properties of cover crops and residue mulches), but also, importantly, there being a change from preemergent herbicides with long residual times in the soil to postemergent herbicides, which are rapidly broken down in the environment. Scopel *et al.* (2004) also argue the latter point, stating that all the facts on the actual use of herbicides and other pesticides (products, rates, frequency of applications) for zero-till should be weighed and compared with that of the conventional systems they are displacing. For example, they argue, whereas rates of 4–5 liter ha^{-1} of atrazine and simazine-based preemergent herbicides were used in conventional maize management in the cerrado region, now, these same types of herbicides are used postemergence in zero-till systems, at early stages of maize development and at rates of 1–2 liter ha^{-1}. Moreover, in the case of soybean, for example, they elaborate, very stable preemergent products have been substituted with more rapidly degraded postemergent ones.

In various calculations of global labor use in zero-till systems compared to conventional systems, based on smallholder farmer surveys in Paraná (Ribeiro *et al.*, 1993; Samaha *et al.*, 1993, 1996, 1998), for example, some of the most significant labor reductions in zero-till are reportedly due to the decrease in time spent on manual weeding and plowing, these operations being replaced by the use of herbicides. There is therefore a tradeoff between the use of herbicides and manual weeding. In a more recent survey among 60 smallholder zero-till farmers in Paraná, Ribeiro *et al.* (2005) found that farmers cultivating labor-intensive crops, such as tobacco, often applied herbicides fairly late and hence witnessed low-herbicide efficacy. Especially farmers that needed to control critical densities of *Spermacoce latifolia* after tobacco and perennial species such as *C. ferax*, *Paspalum* species and *Vernonia polyanthes* commonly resorted to disc harrowing or plowing rather than maintain zero-till, restarting zero-till after weed densities had been effectively reduced. Although herbicides are available and technically effective for control of these species (Lorenzi, 1994; Rodrigues and Almeida,

1998), Ribeiro *et al.* (2005) further stated that mechanical weeding was considered more effective and less costly than herbicide used by interviewed farmers.

In general, their high-relative costs (Petersen *et al.*, 1999), the difficulties experienced by smallholder farmers with herbicide formulation and handling combined with the dearth of farmers resorting to protective clothing for such procedures (Amado and Reinert, 1998; Berton, 1998; Merten, 1994), the presence in zero-till rotations of weed species difficult to control with herbicides and the increasing number of cases of weed resistance (Christoffoleti *et al.*, 1994), and the often negative environmental impacts associated with pesticide use has led to a heightened research of alternative weed management methods on smallholder zero-till farmers in Southern Brazil. Adegas (1998) describes a study of an integrated weed management (IPW) program on 58 farms in Paraná, observing that after 3 years, if optimal recommendations are followed, weed control costs decreased on average by 35% with herbicide reductions of 25%. Ruedell (1995) also details the results of an IPW program in Rio Grande do Sul, where, over an average of 34 areas there was a reduction of 42% in weed control costs assuming farmers follow optimal weed management practices. Such results potentially demonstrate that in theory IPW can prove agronomically, economically, and ecologically beneficial, although it was not clear from these reports if farmers did indeed apply IPW practices themselves under normal circumstances, and if not, why not.

Possibly the major tool in Brazilian IPW under zero-till systems is the use of cover crops. Cover crops are important in weed management mainly for two reasons: first, because they can compete against weeds during their development, and second, after termination of their cycle, their mulch can suppress weed emergence (Almeida *et al.*, 1984; Kliewer *et al.*, 1998; Petersen *et al.*, 1999; Skóra Neto, 1998; Tardin *et al.*, 1998; Thiesen *et al.*, 2000). Considering the first aspect, several winter and summer cover crops have been shown to suppress weeds through their fast growth pattern (Calegari *et al.*, 1993). Favero *et al.* (2001), for example, observed reduction of 22–96% of weed biomass in the presence of summer cover crops varying according the species. Using appropriate cover crop species in a rotation, Skóra Neto and Campos (2004) also noted a weed population reduction of 93% after 3 years. Vasconcelos and Landers (1993) report experiences of planting grain crops into permanent cover crops, of which maize into siratro (*Macroptilium atropurpureum* L. urb.) was the most successful, allowing the complete elimination of the selective maize herbicide. Fernandes *et al.* (1999) observed that *C. breviflora*, *C. spectabilis*, and pigeonpea plots had reduced densities of weeds, while Skóra Neto (1993a) also noted that pigeonpea grown as a companion crop to maize decreased weed infestation at and after the harvesting time; research that was later corroborated by Severino and

Christoffoleti (2004), who remarked that sunnhemp and pigeonpea were effective as smother crops against numerous weed species.

The mulch remaining on the soil can also improve weed management, both through its physical presence on the soil surface and by controlling N availability (Kumar and Goh, 2000) or by direct suppression due to allelopathy (Almeida, 1988; Caamal-Maldonado *et al.*, 2001; Rodrigues, 1997; Skóra Neto and Müller, 1993). Trials at IAPAR showed that black oat, rye, and common vetch residues were capable of suppressing weed emergence after 100 days between 30% and 50% (Table V). Roman (1990) performed similar on-station trials in Passo Fundo, recording the incidence of alexandergrass, arrowleaf sida (*Sida rhombifolia*), and blackjack (*B. pilosa*) infestation through the mulch of 14 common cover crop species after 40 days, finding that black oat, common oat, and ryegrass mulches suppressed all weed species very strongly, while oilseed rape, barley, rye, and a mixture of black oats and common vetch was effective against alexandergrass and blackjack, but not against arrowleaf sida. In general, cover crops species that

Table V
Weed Emergence (Individual Species or General) in Plots Covered with Residues of Various Cover Crop Species, Expressed as Percentage of Weed Emergence in Uncovered Control Plots in Southern Brazil

	Emergence of individual weed species after 40 days at Passo Fundo, PR (Roman, 1990)			
Cover crop residue	*Sida rhombifolia*	*Brachiaria plantaginea*	*Bidens pilosa*	Weed emergence after 100 days, Ponta Grossa, PR (Skóra Neto, 1993b)
Avena sativa	23	0	0	
Avena strigosa	22	0	0	53
Hordeum vulgare	100	17	22	
Lathyrus cicera	87	50	20	
Linum usitatissimum	100	60	90	
Lollium multiflorum	17	0	0	
Lupinus angustifolius				97
Ornithopus sativus	72	55	10	
Raphanus raphanistrum			96	
Raphanus sativa	80	12	0	
Secale cereale	100	11	0	56
Tritico cereale	100	32	0	
Triticum aestivum	100	24	70	
Vicia sativa	100	40	40	66
A. strigosa + *V. sativa*	32	7	0	
Fallow	100	100	100	

produce high amount of residues with a high C to N ratio (i.e., less rapidly decomposed) are more efficient in suppressing weed emergence.

At farm level, the situation is generally more complex, and mulching alone is often only sufficient to minimize weed competition adequately under certain conditions. Skóra Neto *et al.* (2003), for example, recording all inputs and outputs of farmers in five regions of Paraná over 3 years, verified that zero-till crop production without herbicides was possible and economically feasible, but performances were very variable, the best results being obtained only with a combination of good soil fertility, high-cover crop dry matter production, correct main crop populations, and spacing, good timing, and precise planting, while the major drawback or constraint was the amount of labor required for weed control. Jackson (1997) also adds that it is necessary to have implements that allow the farmers to harvest and plant one crop after another nearly simultaneously, thereby encouraging early establishment and competitively of the following crop, but also stresses that having farm labor available to do spot weeding as a management practice is essential. Kliewer *et al.* (1998) reported farm trials conducted in the Alto Paraná region of Paraguay, which, using suitable cover and main crops in rotations over a 3-year period, managed to completely do away with the need for herbicides. They noted that the traditional double-cropping of wheat and soybeans required 11 herbicide applications for adequate weed control, costing over US$200 per ha. Including cover crops in a 2-year rotation (1st year: sunnhemp–wheat–soybean; 2nd year: white lupine–maize), "rolling" the cover crops with a "knife roller" about 50–60 days after seeding and subsequently seeding into the stubble with a zero-till planter improved the situation. This cropping system only required four herbicide applications to manage weeds, which amounted to a total cost of just over US$180 per ha including the cost of cover crop seed and management. A 3-year crop rotation including three cover crops (1st year: sunflower–black oats–soybean; 2nd year: wheat–soybean; 3rd year: lupine–maize) not only eliminated the need for herbicides altogether but also reduced the total cost of weed management to about US$150 per ha. The main reasons for such decreases of weed infestation over time are reductions in weed seed banks, and Skóra Neto (1998), for example, showed an exponential reduction in weed populations when weeds were controlled before seed-set and not allowed to produce seeds.

In summary, empirical results from farmers and researchers have shown that using adequate integrated strategies and cover crops, successful weed management in zero-till is possible with low levels of inputs. The reality on the ground for farmers in Brazil, however, is often more varied and, as, for example results from Skóra Neto *et al.* (2003) and Ribeiro *et al.* (2005) suggest, the great majority of the farmers, especially smallholders in Southern Brazil, still struggle with weed problems and rely on high-herbicides use

or resort to sporadic disc harrowing or even plowing, often not being able to apply the "optimal" recommendations of cover crop and weed control timings proposed by research.

H. Pests and Disease Management

Increased problems with pest and disease "over wintering" in residues are often cited as a major drawback of zero-till: the residues left on the soil surface directly provide a food source and habitat for insects and pathogens in proximity to current or future crop stands, while the indirect effects of residues on soil moisture or temperature may allow certain pests and pathogens to reproduce and spread for longer (Bianco, 1998; Forcella *et al.*, 1994; Nazareno, 1998). Nevertheless, research on the putative effects of zero-till on plant diseases and pests has been rather limited in Brazil (Freitas *et al.*, 2002). Scopel *et al.* (2004), however, note that disease control is a major weak point in zero-till systems in the cerrado region, while they further contend that fungal diseases in wheat, for example, are commonly viewed as problematic by zero-till farmers in Southern Brazil. Breeding programs established by EMBRAPA are focusing on disease resistance in new soybean, rice, wheat, cotton, and maize cultivars exclusively bred for zero-till conditions, and varieties resistant to some of the major disease and pest problems are becoming increasingly available, although, as Freitas *et al.* (2002) argue, these are often not being used by farmers, as susceptible varieties sometimes have other superior agronomic traits. In this context, however, it is important to bear in mind that a residue mulch not only harbors pests and diseases, but also their natural enemies, and the wisest way to tackle pest problems is arguably to apply integrated pest management techniques, for example, where necessary applying carefully considered amounts of inorganic and organic pesticides, resorting to resistant crop species and cultivars, boosting natural pest–predator populations, where possible adjusting sowing date to avoid early infection, avoiding planting susceptible varieties on compact and consequently potentially improperly drained soils, superficial seeding, treating seeds with fungicides, using crops to attract or repel pests, breaking the surface area of a monocrop through intercropping, and, once again, rotating crop species and integrating cover crop species that may help to break pest and disease cycles and/or act as traps for insects and viral vectors. Santos *et al.* (2000), for example, found that sufficient crop rotation, including vetches, black oats, sorghum, soybean, and maize, was efficient in reducing the incidence of root diseases in zero-till maize in Rio Grande do Sul, while Ribeiro *et al.* (2005) state that among a surveyed group of smallholder farmers in Paraná, those farmers growing tobacco faced the most serious challenges in respect to pests and

diseases, and hence were also those that rotated crops most frequently. Yorinori (1996) observed a reduction of *Diaporthe phaseolorum* ssp. *meridionalis* dispersion in soybean by the use of millet as zero-till cover crop, while black oats have been noted to decrease root rot diseases, such as *Fusarium* species, and pigeonpea or sunnhemp have been shown successful in controlling nematodes (Caligari, 1998a,b,c). Viedma (1997) also reported that including vetches mixed with oats into a zero-till rotation relying only on wheat and oats nearly completely eliminated the incidence of *Heliminthrosporium* and *Drechslera* species. Conversely, however, higher incidence of snails and slugs have been noted after crucifers, more thrips after graminae, *Diabrotica* species after hairy vetch (Buntin *et al.*, 1994), caterpillars (*Pseudalentia* spp.) after oats, stemborers (*Listronotus* spp.) after ryegrass (Gassen, 2000), and insects acting as vectors for soybean viruses after a cover crop of *Arachis pintoï* (Scopel *et al.*, 2004), so these crops should be avoided if the associated pest is potentially a threat. A residue mulch may in itself draw insect pests away from growing crops, and Gassen (1999), for example, reported that white grubs (*Cyclocephala flavipennis*), even when present in numbers exceeding 100 larvae m^{-2} did not cause damage to crops as long as sufficient soil cover for them to feed on was present. Freitas *et al.* (2002) also noted that residue mulch decreased the impact of rain drops in dispersing potential pathogen propagules, thereby resulting in less spread of inoculum of, for example, *Diaporthe phaseolorum* ssp. *meridionalis* in the cerrado region. If pests that are restricted in their mobility pose a problem, removing residues from the row and areas of high risk of occurrence may also provide a partial solution.

In summary, although the use of increasingly available crop cultivars resistant to a range of major pests and diseases, as well as astute crop rotation, planting densities, dates and other integrating pest management practices are being used successfully by some farmers in the cerrado and Southern Brazil, pest and disease problems do remain a major challenge in Brazilian zero-till systems and merit further research, both in terms of integrated pest management practices, but also, as Scopel *et al.* (2004) suggest, in terms of the different biocide behavior under zero-till and mulched soils compared to plowed soils.

I. Integrating Livestock and Crops

Small to medium-scale zero-till systems that integrate livestock, both for milk and meat production, but also as a source of drought power, are common in Southern Brazil and typically include high-yielding forage cover crops, such as black oat, common vetch, and ryegrass in winter, or fodder sorghum and mucuna in summer, while large-scale commercially

orientated crop and livestock farms are common in the cerrado. In order to not jeopardize cover crop biomass production, animals on Southern Brazilian smallholder farms are either only permitted onto the fields during strictly controlled periods that allow cover crops to recover and resprout after grazing, or alternatively, the crops are made into hay, silage, or mixed food rations in a cut-and-carry system (Jackson, 1997; Lara Cabezas and Freitas, 2000; cited in Pieri *et al.*, 2002; Ribeiro *et al.*, 2002). Planting contour ridges of vegetative grasses or fodder plants through fields (ideally these should remain vegetative so that they do not set seed in the crop fields), which then serve the dual purpose of providing erosion and runoff control, as well as animal feed, is another common strategy (Darolt, 1998b; Freitas, 2000; Sabourin *et al.*, 2000), and in their proposed steps to facilitate conversion from conventional to zero-till on smallholder farms, IAPAR researchers suggest farmers first initially increase the amount of vegetative grasses grown on contours and set aside land throughout the farm, which would then serve to feed livestock and thereby decrease grazing pressure on residues, subsequently evaluating different spatial arrangements and planting densities over the whole farm before abandoning tillage and moving toward proper zero-tillage. Common contour species in Southern Brazil include elephant, king or cameroon dwarf and giant varieties of napier grass (*P. purpureum*), phalaris (*Phalaris hibrida*), sugarcane (*Sacharum officinarum*), lemon grass (*Cymbopogon citratus*), pigeonpea, or sometimes vetiver grass (*Vetiveria zizanioides*), which is reportedly particularly efficient in erosion control (World Bank, 1990), the type of vegetation chosen by farmers for contouring depending mainly on the number of animals that have to be fed, the labor available to manage it and other agricultural production priorities on the property. For the seasonally dry cerrado region, Séguy *et al.* (1996) suggest planting napier grass, bana grass (a sterile hybrid of napier grass and *P. typhoides*), or *Tripsacum laxum* on contours. If land for cropping is at a premium, intensive fodder banks or gardens on small plots of land either set aside or on marginal parcels and strips that are unsuitable for annual cropping, such as along fence lines or around cattle pens, and so on, are used. Especially in the semiarid northeast of Brazil, such feed gardens or *capineiras* of napier grass, forage cactus (*Opuntia* spp.), or gliricidia (*Gliricidia sepium*) are widespread on smallholder farms (Menezes *et al.*, 2002; Sabourin *et al.*, 2000).

In the seasonally dry cerrado region, ley systems, where forage land is set aside and grazed for 3–4 years, are common. When the unfertilized pasture becomes nitrogen deficient, the land is bought back into legume or fertilized crop production, and a new parcel of land set aside for grazing. *Brachiaria* and *Stylosanthes* species have been shown to be both efficient in recycling nutrients and as good forage species in the cerrado (Scopel *et al.*, 2004). If grown as cover crops toward the end of the rainy season, they can be grazed

as soon as at the beginning of the following dry season. Moreover, due to their large biomass production, successions of *Brachiaria* and *Stylosanthes* species with commercial crops offer the possibility building SOM levels and rehabilitating degraded pastures at basically no installation costs (Scopel *et al.*, 2004), while Broch *et al.* (1997) found that such systems can support soybean yield increases over a number of years. Kluthcouski *et al.* (2000) describe the "Santa Fé" cropping system in the cerrado, which mixes a maize crop and a brachiaria pasture. The brachiaria is made to germinate and emerge later than the maize, either by delaying its planting or by planting it deeper. During the whole maize cycle, the brachiaria is shaded by maize plants and remains minimally competitive to the maize, but at maize harvest, the pasture is already in place, and grows very quickly over the maize residues. The brachiaria is then killed with a desiccant herbicide, with rates varying from about 2 liter ha^{-1} of glyphosate on *B. ruziziensis* to over 4 liter ha^{-1} on *B. brizantha*, with *B. decumbens* at an intermediate level, and soybean is planted directly into the dead/dying brachiaria sward, the zero-till planter breaking through the superficial compaction layer (8–10 cm) of the pasture (Landers, 1998). Similar types of systems have been devised in Southern Brazil, including a rotation of ryegrass used as pasture during winter followed by a soybean crop planted directly on the chemically desiccated ryegrass (Scopel *et al.*, 2004). This tight integration between forage and grain crops generally leads to a better use of total farm land and a more intensive use of the pastures, with shorter turnover and less pasture degradation.

J. Suitable Equipment for Resource-Poor Farmers

As the first Brazilian-built zero-till planters were only commercially available from 1975, many pioneer farmers started zero-till by transforming their conventional equipment, and a great variety of equipment evolved (Derpsch, 2001). Today, however, about 15 companies in Brazil build zero-till equipment (Derpsch, 2001), some of which are now among the world leaders in the production of zero-till equipment. A large variety of equipment for various operations, farm sizes, soils, crops, and levels of mechanization exists. However, while some of the more sophisticated machinery is in principle similar to that produced elsewhere in the world and a detailed description thereof beyond the scope of this chapter, what is perhaps unique in Brazil is the large variety of implements suited for smallholder farmers, designed for light mechanization, animal drawing, or hand operation. Although many Southern Brazilian farmers may purchase expensive equipment in group or associations, subsequently sharing its cost and use (Freitas, 2000), examples

of smallholder operations in Southern Brazil demonstrate that zero-till and cover crop management can be practiced by individual farmers at all levels of mechanization and without extensive capital outlays. While much of such equipment is detailed in IAPAR publications (IAPAR, 1981, 1993, 1998), we would like to refer interested readers to Freitas (2000) or Pieri *et al.* (2002), for example, where a variety of relatively low-cost zero- and minimum-till planters, crop rollers, and sprayers are presented in English-language publications, instead restricting our review here to the principles behind animal-drawn or hand-operated zero-till planters and knife-rollers that have been developed in Brazil.

Especially important for Brazilian-type zero-till are implements that allow for timely planting of crop in order to optimize early growth and minimize competition from weeds, as well as maximize the crop's weed-smothering potential at the appropriate time. Probably the best-known and best-proven zero-till implement for smallholder farmers on steep land is the hand-held, V-shaped jab planter, known as "matraca" in Southern Brazil. This simple utensil has now been in use for decades in South America for the manual seeding of large areas (Steiner, 1998), can easily be adapted for various conditions and seed types, and exists in versions that include a fertilizer holder, thereby allowing fertilizer granules to be applied at the time of seeding (Araújo Almeida, 1993). More sophisticated planters include a series of animal-drawn zero-till planters derived from the "Gralha Azul" prototype, originally conceived by IAPAR. Basically, these planters are equipped with weighted discs that cut through trash to open narrow seed furrows, as well as a seeding and fertilizer element and seed and fertilizer containers. The seed is placed behind the discs directly into the furrows, usually together with fertilizer in a way that it does not come into direct contact with the seed, while the soil is subsequently recompacted by the rubber wheels that follow the seeding elements and allow the working depth to be controlled. Drilling or banding the fertilizer close to the seed means that germinating seed can get its radicle to the fertilizer in relatively short time, and in the case of nutrients that are important very early in the crop's life cycle, also means that the crop seed will get a head start over weeds in a low-fertility system. In general, direct subsurface placement of fertilizer also greatly increases fertilizer efficiency and decreases amounts required by avoiding excessive volatization or adsorption of fertilizer nutrients onto soil particles. The "Gralha Azul"-type of planter has proved especially popular in the Southern Brazilian states of Santa Catarina and southern Paraná, where the often hilly topography restricts mechanization, thereby making the use of animal traction and manual labor frequent (FAO/INCRA, 1995). There are now over 10 models of the "Gralha Azul," which differ in their suitability to heavy or light soils, residue amounts, steepness of the topography, and so on (Ribeiro, 1998). Darolt (1998b)

suggests that animal traction can be used on land with a slope of up to 30%, while steeper slopes are more suited for planting using a matraca. A similar type of zero-till planter now produced by four manufacturers in Brazil is well suited to stony soils (Ribeiro *et al.*, 2000).

Another implement innovation that has been refined through adaptive experimentation and trialing by Brazilian farmers is the "knife-roller" ("rolo faca" or small Argentine roll) designed to crush or break and roll cover crops. Although a knife roller commonly comprises a cylinder with blades to be drawn by an animal or a small tractor, versions in Brazil range from simple weighted pieces of wood that crush plant stands when towed through them (mainly useful when plant biomass is not very high), to complex cylinder-and-disc systems attached to the front or rear of tractors (Araújo *et al.*, 1993, 1998; Freitas, 2000). Apart from reducing the reliance on herbicides to terminate cover crops, rolling also has the advantage that residues are knocked down in the direction of rolling, thereby facilitating planting, but also, as described previously (Section III.A), that the whole plant remains intact and attached to the soil, thereby preventing dispersal of loose residue by wind and during planting operations, and decreasing residue decomposition rate, consequently extending the effectiveness of the residue cover to suppress weed growth. The timing of the rolling operation is however crucial to its success, as most plant species can regenerate if they are rolled or slashed prematurely, while mature seeds of the cover crop or weeds may set and germinate if elimination is carried out too late (Skóra Neto, 1998; Skóra Neto and Darolt, 1996). Trials to this respect indicate that the best time to roll grasses is at the milky grain phase, while in legumes this is best done at the beginning of pod formation or full flowering, depending on the species (Ashford and Reeves, 2003; Calegari, 1998a).

IV. CONCLUDING REMARKS

A great wealth of zero-till technologies applicable to a variety of scenarios has accumulated in Brazil, and some of the basic stereotypical zero-till systems of Brazil are presented in Table VI.

Two decades of extensive adaptive research and experimentation with reduced tillage methods has allowed farmers and researchers to mature zero-till into a holistic intertwining of soil and crop management techniques, involving no soil turning, rigorous maintenance of a permanent vegetative cover, and judicious rotations of both cash and cover crops, thereby giving rise to "ideal" zero-till systems suited to a variety of conditions. Brazilian research clearly demonstrates that under the right conditions, it is possible to practice successful zero-till on a variety of soils commonly deemed

Table VI
Stereotypical or "Model" Brazilian Zero-Till Systems (Partially Based on Calegari, 2002; Scopel *et al.*, 2004)

Systems	Physical conditions	Basic cropping regimes	Reported advantages	Reported challenges
Large-scale farms in the Cerrado (>100 ha) Mechanized grain and livestock production	Seasonally dry, humid tropics; Deep, acidic Oxisols; Flat to undulating topography	During rainy season: soybean, maize, rice, cotton, or beans At end of rains/over dry season: deep-rooted cereals, such as millet, maize, sorghum, often in combination with an undersown, drought tolerant fodder or forage cover crop	Erosion control; Nutrient recycling; Increase in SOM; Organization of farm activities	Technical management of certain crops (rice, cotton); Disease control
Large-scale farms in Southern Brazil Mechanized grain and livestock production	Humid subtropics; Clayey Oxisols and Alfisols to sandy Ultisols; Undulating topography, sometimes with steep slopes	In spring/summer (main growing season): commercial crops such as maize and soybean In the "safrinha"/winter season: black oats, wheat, ryegrass, common or hairy vetches, oilseed radish, rye, white or blue lupines, grown alone or as mixes		Disease control; Negative effects of certain rotations (e.g., allelopathic effects on succeeding crop, and so on)
Smallholder farms in Southern Brazil (<50 ha) Low levels of mechanization and external input use, commonly animal traction. Crop and livestock production		In spring/summer: maize, beans, tobacco, onion, garlic, potatoes, rice, cotton, and soybean In the "safrinha"/winter season: black oats, common or hairy vetches, oilseed radish, rye, white or blue lupines, and ryegrass, grown alone or as mixes. Many fallow fields if they cannot afford cover crop seed, while some grow wheat as cash crop	Labor and external input savings; Erosion control; Increased crop yields	Weed control; timely labor and input management; No markets for diversifying crop rotations; Cover crops seed production or affordability

unsuitable for zero-till, and that by exploiting rapid successions of suitable summer and winter crop and cover crops, in combination with careful temporal and spatial planning, it is possible to continuously cover soil, gradually build-up SOM, benefit from residual nutrient effects, successfully integrate livestock, move surface-applied lime through the soil profile without plowing, and break up compact soil layers, among other things. Suitable rotations, timing, spacing, and fertility conditions in combination with implements, such as zero-till planters and knife-rollers of various levels of sophistication, have further been shown to allow herbicide and pesticide use to be reduced or even, in the best case scenarios, to be eliminated over a certain timeframe.

However, such systems represent the "ideal," and in order for farmers to effectively reap the full benefits of zero-till, appropriate systems must simultaneously combine and integrate many of the different ideal technologies and components. Rather than resort to the complete combination of all such technologies, most Brazilian farmers on the ground, on the other hand, incorporate the various zero-till components into their practices to a greater or lesser extent according to their socioeconomic, cognitive, and biophysical situation: although farmers practicing ideal or model zero-till systems certainly exist, this is probably not true for the majority of farmers, especially not for the majority of resource-poor smallholder farmers in Southern Brazil, who struggle to afford cover crops seed or herbicides, who resort to periodical plowing to combat mounting weed pressure or incorporate lime, who may not be able to employ the right amount of labor at the right time, or who are simply limited to growing sequences of cash crops rather than optimal rotations of main and cover crops due to economic necessity in the lack of subsidies or other income-generating activities, for example. In this context, we stress that although Brazilian zero-till harbors many useful lessons on how to surmount obstacles commonly associated with zero-till, many challenges to successful zero-till remain.

Additionally, although undoubtedly numerous advances in zero-till research has accrued in Brazilian research over the past 20 years, much of this research has been based on experimental conditions in optimal settings, studying individual technologies rather then more complex whole-farm systems with all the flaws such a setting may bring with it. Consequently, there is somewhat of a divorce between some of the research innovations and results and farmers' reality. Although researching ideal technologies is undoubtedly invaluable in formulating general guidelines for what method induces what effect, future research should perhaps increasingly also consider the effects of less optimal but more realistic intermediate systems that may include periodical plowing or suboptimal rotations when the need arises.

In conclusion, the wealth of high-quality research data and farmers' experience on various Brazilian zero-till techniques precipitating out of

the Brazilian zero-till revolution can certainly inspire and afford us potential guidelines along which we can seek solutions and directions for successful zero-till in many other parts of the globe. We must, however, bear in mind the true context of these innovations and technologies in order to realistically assess them in the right light.

ACKNOWLEDGMENTS

The authors are deeply indebted to Dr. Dirk Claudio Ahrens of the Agricultural Research Institute of Paraná (IAPAR), Mr. John Landers of the Zero-Tillage Association of the Cerrado (APDC), and Dr. Martial Bernoux of the Institut de Recherche pour le Développement (IRD) for the kind and generous provision of extra insight and information.

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MECHANISMS AND PATHWAYS OF TRACE ELEMENT MOBILITY IN SOILS

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Advances in Agronomy, Volume 91

0065-2113/06 $35.00
DOI: 10.1016/S0065-2113(06)91003-7

ABBREVIATIONS

TE Trace element
EPA Environmental Protection Agency
CEC Cation exchange capacity
DOM Dissolved organic matter
OM Organic matter
EDTA Ethylenediamine tetracetic acid
NTA Nitrilotriacetate

I. INTRODUCTION

Trace elements, hereafter referred to as TEs, are a major group of contaminants worldwide arising from natural and anthropogenic sources. In the modern era, the anthropogenic sources arising primarily from industrialization have assumed paramount importance in the quality and sustainability of ecosystems (Adriano, 2001). The main anthropogenic sources include mining and smelting of metallic ores, combustion of coal and other fossil fuels, use of pesticides in agriculture and timber industry, manufacturing, landfills, and so on.

While certain TEs have essential biological functions in plant, animal, and human nutrition (such as the essential micronutrients Fe, Zn, Cu, Mn, Mo, and B in plant nutrition and Se, $Cr_{(III)}$, Ni, and so on in animal and human nutrition), others (such as Cd, Hg, Pb, and to a large extent As) have no known biological functions whatsoever (Adriano *et al.*, 2004). In fact, Cd, Hg, Pb, and As are on the EPA's list of priority pollutants because of their widespread and intense occurrence at waste sites and their known detrimental effects on ecological and human receptors (EPA, 1995).

The importance of TEs in soils depends largely on their fraction that has immediate biological function, that is, the fraction of the total soil burden that is soluble, mobile, and bioavailable. The nature and extent of mobility and bioavailability underlines the integrity and sustainability of a particular environment and in particular, the role of TEs in the functioning and well-being of an ecological endpoint (Allen, 2002; NRC, 2003). In an impacted ecosystem, the potential risks of TEs to ecological and human receptors largely depends on several factors, which primarily include site and waste characteristics, source term and chemical properties of the contaminants including chemical speciation, geo-hydrological characteristics of the site,

diversity of ecological receptors, and climate. These factors, to a large extent, influence the magnitude and intensity of solubility, mobility, and bioavailability of TEs. Thus predicting mobility and bioavailability of TEs in the soil environment is critical yet quite complicated. Generally, a TE in soil has to be mobile before it can become bioavailable to plants and other soil biota.

As indicated earlier, contaminants, such as TEs, need to be mobile and bioaccessible to organisms to be beneficial or detrimental, they would also need to be mobilized to eventually reach a surface body of water or to be leached to underlying ground water. It then appears that, generally speaking, to be of any consequence to ecological receptors, a TE should have a distinct characteristic of being mobile first and secondly of being bioaccessible and/or bioavailable to organisms (Semple *et al.*, 2004). These processes and their associated mechanisms underline the thrust of biogeochemical cycling of TEs in the environment.

This chapter covers the basic mechanisms in the solubility and mobility of the TEs in the soil, including their movement in the soil profile, the entire vadose zone and the eventual leaching to the ground water. In essence the mechanisms influencing the extent of TE partitioning between the soil's solid and aqueous phases are elucidated in Section II. This leads to the various transport pathways (Section III) in soil responsible for disseminating TEs in the form of gaseous (volatilization), aqueous (soluble solute), colloids, and particulate matter. Then the most pertinent factors influencing the partitioning and movement of TEs are discussed. And finally, transport modeling of the most environmentally important TEs (Section V) and their applications (Section VI) typified by field case studies are illustrated. Transport modeling in the vadose zone is emphasized.

II. MECHANISMS OF TRACE ELEMENT MOBILITY

There are basic physical, chemical, and biological processes that control mobility of TEs in soils. The first major group can be lumped into physicochemical processes (see in a later section) that promote and regulate mechanisms such as solubility and precipitation, adsorption, complexation, and occlusion/encapsulation. The processes that sequester TEs can be grossly termed sorption which, to a large extent, determines the partitioning between the solid and solution phase. These processes can be expected to predominate in severely metal-contaminated soils as biological processes could be limited by the toxicity of the metals of concern.

A. Physicochemical Processes

The majority of TEs in soils usually occur in association with the solid phase, where they can be bound to the surface of the soil's solids, or they can

be precipitated as various minerals or simply be coprecipitated within various forms. For most TEs, only a small portion is dissolved in the soil solution; most of the dissolved TE is bound to organic acids in the soil solution, the remainder being distributed as inorganic ion pairs and free ions. This free ion pool is usually quite small relative to the other TE pools, but it is the most reactive, chemically and biologically. Thus it is critical in understanding the mobility, transport, and fate of TEs in soils.

Figure 1 illustrates the implications of fractionation and speciation of Cd in a hypothetical soil contaminated with 1 mg Cd per kilogram dry soil with a pH of 5. The proportion of Cd atoms is correctly scaled to represent the relative importance of the various metal pools. The actual occurrence of Cd associated with the solid phase is clearly predominant (◇). Furthermore, the importance of complexation with organic ligands (▲) or the formation of inorganic ion-pairs (□) shows that a tiny proportion of the Cd in this soil actually occurs as free Cd^{2+} in solution (☆) while most of it is not very reactive. This figure illustrates vividly that the proportion of the TE bound to the solid phase predominates in this system. When the pH is elevated from 5 to 7 there would be about 100-fold more Cd on the solid phase. If Pb, generally an immobile TE, is substituted for Cd, a relatively mobile TE, the binding to the solid phase would also be about a 100-fold stronger (cumulative with any pH effects, e.g., $\sim 10^4$ times stronger binding by changing Cd in Fig. 1 to Pb at pH 7).

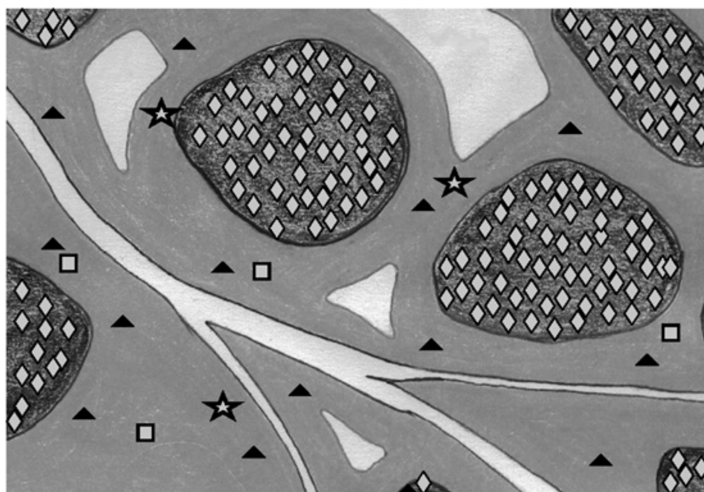


Figure 1 Fractionation and speciation of Cd in a hypothetical soil contaminated with 1 mg Cd kg^{-1} dry soil at pH 5. The distribution of Cd atoms is proportionally scaled to represent the relative importance of the various metal pools; bound to the solid phase (◇), complexed with organic ligands (▲), associated with inorganic ion-pairs (□), or occurring as free Cd^{2+} in solution (☆). Adapted from Sauvé (2003a).

The diagram (Fig. 1) illustrates the effect of solution pH and type of the element on the chemical speciation of the TE in question, providing some insight as to the potential mobility of that element.

1. Mineral Solubility and Precipitation

Soils can be viewed as a mixture of discrete aluminosilicate minerals, precipitated minerals, and partially decomposed and transformed organic matter residues. Within the soil solution phase, anytime a chemical element exceeds its solubility for a given compound, this mineral could precipitate. Likewise, when the solution concentration of a given component of the mineral phase is below its chemical equilibrium concentration, it could dissolve until the concentration increases to attain this equilibrium concentration. The dissolution–precipitation process, depending on a myriad of factors, can be expected to be slow in most cases.

It is not uncommon for minerals to first precipitate as amorphous materials, then undergoing slow transformation to a more crystalline form. Coprecipitation of TEs can easily occur within the newly formed matrix of common soil components such as carbonates, hydroxides, phosphates, metal (Fe, Mn, and Al) oxides, and others. These reactions can be expected to occur commonly in soils and can be considered as major mechanisms to sequester TEs, limiting their mobility and bioavailability to biota. For example, in alkaline, calcareous soils, TEs can be occluded in the carbonate phase (Adriano, 2001); in highly fertilized agricultural soils, TEs can be sequestered when they coprecipitate with phosphates; and in highly weathered oxidic soils, TEs can be immobilized by the metal oxides. Combined, these sequestration processes could induce an attenuation of metals to levels considered acceptable by regulatory standards by virtue of decreased risk (Adriano, 2001). However, in heavily contaminated soils significant proportions of the total TE mass can be solubilized and eventually mobilized, or simply occur as TE-based mineral phase. A classic example is the occurrence of Pb pyromorphite, a highly stable, immobile mineral in soils heavily contaminated with Pb in the presence of phosphate (see also Section IV.D).

The solubility of standard mineral forms is much easier to evaluate and predict than the interaction with coprecipitating minerals. The data needed to evaluate the solubility of TEs are, for the most part, available in the literature and the principal mineral forms for some often-observed TEs are compiled in Table I. It is easy to use these compiled constants in evaluating the extent of solubility of the mineral forms of a given TE in a contaminated soil.

Figure 2 illustrates this for Cd, Cu, and Pb where the dots represent experimentally measured free metal ion activities and the lines the equilibrium concentrations for various TE minerals in an oxidic soil. For the Cd-contaminated soils in this figure, in all cases, the free Cd^{2+} activities in the

Table I
Selected Chemical Equilibrium Constants for Various Cd, Cu, and Pb Minerals[a]

Equilibrium reactions	log *K*
Cd minerals	
$\beta - Cd(OH)_2(c) + 2H^+ \Leftrightarrow Cd^{2+} + 2H_2O$	13.74
$CdCO_3(octavite) \Leftrightarrow Cd^{2+} + CO_2(g) + H_2O$	6.16
$CdO(monteponite) + 2H^+ \Leftrightarrow Cd^{2+} + H_2O$	15.14
$CdSO_4(c) \Leftrightarrow Cd^{2+} + SO_4^{2-}$	−0.11
$CdSO_4 \cdot 2Cd(OH)_2(c) + 4H^+ \Leftrightarrow 3Cd^{2+} + SO_4^{2-} + 4H_2O$	22.65
$Cd_3(PO_4)_2(c) + 4H^+ \Leftrightarrow 3Cd^{2+} + 2H_2PO_4^-$	1.00
$CdSiO_3(c) + 2H^+ + H_2O \Leftrightarrow Cd^{2+} + H_4SiO_4^0$	7.63
Cu minerals	
$Cu(OH)_2(c) + 2H^+ \Leftrightarrow Cu^{2+} + 2H_2O$	8.68
$CuCO_3(c) + 2H^+ \Leftrightarrow Cu^{2+} + CO_2(g) + H_2O$	8.52
$Cu_2(OH)_2CO_3(malachite) + 4H^+ \Leftrightarrow 2Cu^{2+} + CO_2(g) + 3H_2O$	12.99
$Cu_3(OH)_2(CO_3)_2(azurite) + 6H^+ \Leftrightarrow 3Cu^{2+} + 2CO_2(g) + 4H_2O$	19.59
$CuO(tenorite) + 2H^+ \Leftrightarrow Cu^{2+} + H_2O$	7.66
$Cu_4(OH)_6SO_4(bronchantite) + 6H^+ \Leftrightarrow 4Cu^{2+} + SO_4^{2-} + 6H_2O$	15.35
$Cu_3(PO_4)_2 \cdot H_2O(c) + 4H^+ \Leftrightarrow 3Cu^{2+} + 2H_2PO_4^- + 2H_2O$	0.34
Pb minerals	
$Pb(OH)_2(c) + 2H^+ \Leftrightarrow Pb^{2+} + 2H_2O$	8.16
$PbCO_3(cerussite) + 2H^+ \Leftrightarrow Pb^{2+} + CO_2(g) + H_2O$	4.65
$Pb_2(CO_3)_2(OH)_2(hydrocerussite) + 6H^+ \Leftrightarrow 3Pb^{2+} + 2CO_2(g) + 4H_2O$	17.51
$PbO(red) + 2H^+ \Leftrightarrow Pb^{2+} + H_2O$	12.72
$PbSO_4(anglesite) \Leftrightarrow Pb^{2+} + SO_4^{2-}$	−7.79
$PbHPO_4(c) + H^+ \Leftrightarrow Pb^{2+} + H_2PO_4^-$	−4.25
$Pb_5(PO_4)_3OH(hydroxypyromorphite) + 7H^+ \Leftrightarrow 5Pb^{2+} + 3H_2PO_4^- + H_2O$	−4.14
$Pb_5(PO_4)_3Cl(chloropyromorphite) + 6H^+ \Leftrightarrow 5Pb^{2+} + 3H_2PO_4^- + Cl^-$	−25.05

[a]Sources: Carroll *et al.*, 1998; Lindsay, 1979.

soil solution are much below the potential chemical equilibrium; thus it is clear that the solubility and mobility of Cd in soils is not controlled by chemical solubility equilibrium with a mineral phase. Rather the various sorption or coprecipitation mechanisms could control the solubility of Cd. The case for Cu is somewhat intermediate, with most of the soil data well below the solubility equilibrium of potential mineral phase, except for the most critically contaminated soils where few samples close or above the least soluble mineral form are represented by a set of soils contaminated with more than 10,000 mg Cu kg^{-1} dry soil. It indicates that only in the case of an extreme contamination is a mineral phase likely to control Cu solubility. In the case for Pb, quite a few points are clustered around the solubility line for chloropyromorphite [$PO_5(PO_4)_3Cl$] given that some of these soils are contaminated with only 1000 mg Pb kg^{-1} dry soil. This implies that mineral solubility could, in some situations, control the solubility of Pb in contaminated soils. Indeed, chloropyromorphite formation has been observed in contaminated soils (Ryan *et al.*, 2004) and can actually be used to limit

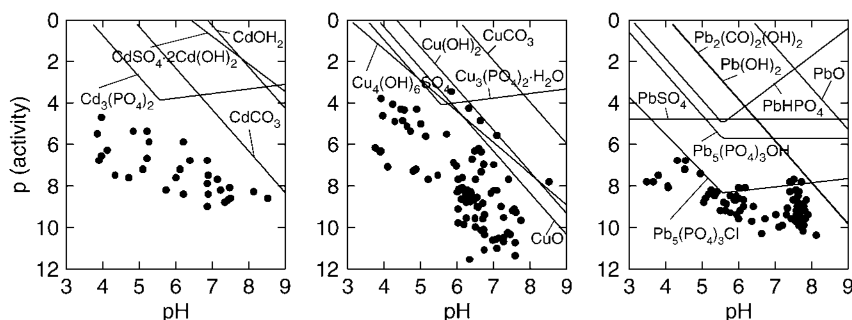


Figure 2 Soil solution mineral solubility equilibria for Cd, Cu, and Pb. The solid lines represent the theoretical free-metal ion activity maintained at equilibrium by various mineral phases. The computations assume 0.005 M Cl^-, 0.001 M SO_4^{2-} and NO_3^-, atmospheric CO_2, 0.01 M Ca and PO_4^{3-} solubility controlled by $FePO_4$ below pH 5.6 and by $Ca(PO_4)_3OH$ at higher pH values. The dots represent actual electrochemical speciation measurements in field-collected contaminated soils (Sauvé, 1999; Sauvé *et al.*, 1997a,b, 2000b). Reproduced from Sauvé (2003b) pending permission.

mobility and bioavailability of Pb in soils (Berti and Ryan, 2003; Ryan *et al.*, 2004).

In other words, when soils become heavily contaminated with metals, metal solubility may reach a level to cause precipitation. In addition, precipitation may occur in the vicinity of phosphate fertilizer zone or in the vicinity of carbonates and/or alkaline waste by-products. In reducing environments where the sulfide concentration is sufficiently high, precipitation of TEs as sulfides may have a significant role in metal dynamics.

2. Partitioning

The simplest means to represent partitioning of TEs between the solid–liquid phases in soils is to use a K_d coefficient. This is a gross expression of TE interactions between phases. In other words, it is a result of the degree of association or dissociation of the TE from the solid phase. The coefficient is usually expressed as the ratio of the sorbed metal on the solid phase relative to the amount of dissolved metal present; therefore, the higher the K_d values the higher the sorption to the solid phase and the lower the solubility.

$$K_d = \left(\frac{\text{sorbed metal}}{\text{dissolved metal}}\right) \tag{1}$$

where sorbed metal is usually given in $mg{\cdot}kg^{-1}$ and dissolved metal in mg $liter^{-1}$, hence the units for K_d's are in liter kg^{-1}. Standard sorption experiments that model metal sorption using a single-value K_d approach presume

that the sorption capacity of a material is relatively independent of soil physicochemical properties. However, the dependence of K_d's on soil texture and soil organic matter content is well recognized (Buchter *et al.*, 1989; Sauvé *et al.*, 2000b, 2003) and attempts have been made to delineate data into various soil textural categories (Sheppard and Thibault, 1990). Although some default values are available for a large number of elements (Anderson and Christensen, 1988; Buchter *et al.*, 1989; Gooddy *et al.*, 1995; Sauvé *et al.*, 2000b, 2003; Sheppard and Thibault, 1990), many values had to be estimated from plant/soil/solution relationships which rely on simplified assumptions (Sheppard and Evenden, 1988; Sheppard and Thibault, 1990). Furthermore, there is ample evidence that single-value K_d's are not appropriate to represent metal solubility in soil chemistry models (Jopony and Young, 1994; Sauvé *et al.*, 2000b, 2003) and some considerations for chemical properties, such as pH (Fig. 3) (see more detailed discussion in Section IV.A), organic matter, and total metal burden, need to be considered (Janssen *et al.*, 1997; Jopony and Young, 1994; Sauvé *et al.*, 2000b, 2003).

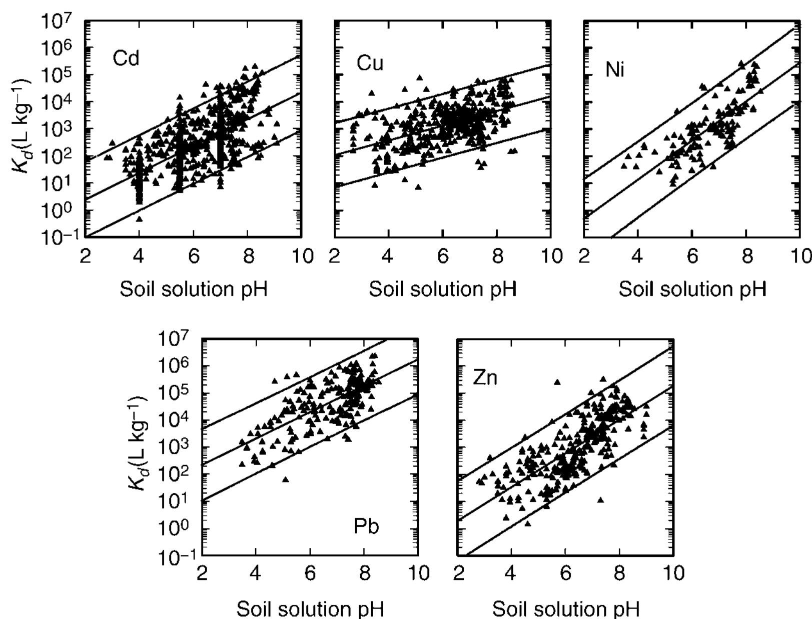


Figure 3 The partitioning coefficient (K_d) as a function of soil solution pH for Cd, Cu, Ni, Pb, and Zn data. Results were calculated from the compilation of Sauvé *et al.* (2000b). The upper and lower lines represent the 95% prediction intervals. Reproduced from Environmental Science and Technology 2000, 34:1125–1131, *pending* permission from the American Chemical Society.

a. The Freundlich Isotherm. The Freundlich isotherm considers the effects of saturation of sorbing surfaces. Relative to the single-value K_d approach, an n parameter is introduced to allow for variations in the K_d values according to the relative saturation of the sorbing surfaces. Hence, as the solution concentration of the metal increases, the ratio adsorbed on the solids will vary. The Freundlich equation takes the form:

$$(\text{Sorbed metal}) = K_d(\text{dissolved metal})^n \quad (2)$$

where the units are the same as in (1) in the case where the value of the constant, n, is 1. The relationship between adsorbed and dissolved metal is illustrated in Fig. 3. Also, Buchter *et al.* (1989) have measured Freundlich parameters (K_d and n) for 11 different soils and 15 TEs. They also explored the correlation of the Freundlich parameters with selected soil properties and found that the pH, cation-exchange capacity (CEC) and Fe/Al oxide contents were the most important factors for correlation with the partitioning coefficients. Buchter *et al.* (1989) observed the following results.

1. pH is the most important soil property that affects K_d and n.
2. Cation-exchange capacity substantially influences K_d for cation species.
3. The amounts of amorphous Fe and Al oxides, and amorphous materials in soils influence both cation and anion retention parameters.
4. Except for Cu and Hg, transition metal (Co and Ni) and group IIB cations (Zn and Cd) have similar K_d and n values for a given soil.
5. Significant relationships between soil properties and retention parameters exist even in a group of soils with greatly different characteristics.

Corroborations by other recent studies (Anderson and Christensen, 1988; Gooddy *et al.*, 1995; Janssen *et al.*, 1997; Jopony and Young, 1994; Lee *et al.*, 1996; McBride *et al.*, 1997b; Sauvé *et al.*, 2000b, 2003) suggest that metal partitioning between the solution and the solid phase in contaminated soils could be, at least to some extent, predicted from common soil properties.

Buchter *et al.* (1989) suggested that certain groups of TEs could have similar sorption properties in a certain soil. They also found that the Freundlich parameter n varied experimentally from $\sim$0.4 to $\sim$1.5 for 15 different chemical elements, indicating that different elements have different sorption properties. For example, comparing the behavior of Pb and Zn, higher concentrations of Pb in solution could promote its adsorption, increasing the apparent K_d (case of $n > 1$). For Zn on the other hand, higher solution concentrations could decrease the apparent K_d, reflecting lower affinity of the solid phase for Zn as it moves toward saturation ($n < 1$). Thus it is not advisable to use K_d values derived under low-contamination levels and use them for risk assessment modeling of contaminated conditions (or reverse).

Most of the elements studied by Buchter *et al.* (1989) have an *n* parameter below 1, and should therefore react qualitatively like Zn (except for Pb and possibly Hg).

The comparison of the K_d values derived from mineral soils are also quite different from that of organic soils (Sauvé *et al.*, 2003). If one intends to use a K_d approach for estimating metal mobility or transfer in the environment, corrections for pH and organic matter content could be critical and coefficients derived from a given dataset could only be appropriate for interpolation within the physicochemical parameters of that dataset but should not be extrapolated outside those parameters.

3. Complexation

Complexation of TEs is ubiquitous in both aquatic and terrestrial systems, especially for trace metals (e.g., Pb, Zn, Cd, Hg, Cu, and so on). In most situations, a significant proportion of the soluble metals occur in association with dissolved natural organic matter (DOM). This DOM is composed of an heterogeneous mixture of fulvic and humic acids (Stevenson, 1994). Given that these natural ligands occur at rather large concentrations in soils and have variable chemical composition and structure, complexation with natural organic acids is rather difficult to model.

Complexation can be subdivided among weakly bound ion pairs (an example of outer-sphere complex formation), complexes (an example of inner-sphere complex) and strong ligands. Ion pairs often refer to electrostatic interaction of a metal with an inorganic anion where, for the most part, the hydration shells of the ions are largely unaffected. With complexation, some of the bonding is covalent and the hydration shells of the ions are reduced. Whereas with chelate ligands metals usually posses more than a single binding site and with little, if any, of the hydration shell retained. Weak ion-pairs with inorganic anions are rather easier to model, so is binding with strong ligands having clear and definitive structure. Overall modeling of complexation with DOM is quite challenging because of the heterogeneity and variable chemical composition of the organic substance.

A further complication is that chemical equilibrium models can indeed be used to calculate the complexation of metals with natural organic ligands, given that one has the appropriate stability constants for the metal binding affinity of the natural organic matter actually present in the matrix under study. Various computer models are available to calculate the solution speciation of metals (e.g., GEOCHEM, SOILCHEM, HYDROQL, ECOSAT, MINTEQ2, WHAM, PHREEQC, and so on). Inasmuch as these models are used to calculate the speciation or partitioning among inorganic chemical species, which model is applied has very little influence on the end result.

In modeling metal complexation by DOM, the actual stability constants used and model assumptions can have a larger influence on the results. Unfortunately, a majority of the data available for those constants are derived from titration data where large metal concentrations are added to purified organic acids of mostly aquatic origin. The purification protocol, which is desired to produce consistent experimental results transforms the properties of the fulvic and humic acids. Furthermore removing cations not included in the study can render the results unrealistic, misrepresenting DOM occurrence under field conditions. However, recently various chemical models, called surface complexation models, have been used to describe B adsorption, in which molecular features, specific surface complexation, chemical reactions and charge balances are considered. The prediction of adsorption on the soil using such models has been successful for B, Mo, Mn, and As (Goldberg, 2004, 2005; Goldberg and Forster, 1998; Goldberg *et al.*, 2002).

Even more difficult to integrate in those chemical *equilibrium* models is that by definition, they fail to account for the slow kinetics of some of these reactions and this is an area of research that needs to be further expanded, especially in soil environments where complexation of a particular TE may be slowed and hindered by the need to displace cations, such as calcium or magnesium, from the ligands before complexation can take place. Many factors need to be considered when trying to model and predict complexation of TEs in soils and those are further discussed in Section IV.

B. Biological Processes

In typical, uncontaminated soils, biological processes are usually mediated by microbes, invertebrates, and plant roots. However, in severely contaminated soils the metal toxicity limits the importance of biological organisms. Thus, it is not uncommon to find derelict old mining sites largely nonvegetated with less biodiversity in soil microbes (González Chavez *et al.*, 2005) and invertebrates such as worms, nematodes, and so on. However, once soil amendments are added to soils to create a more favorable growth environment to these organisms, biological processes can assume major importance in the attenuation of metals. In typical soils, biological processes are more predominant in the top soil since the majority of the microbial and invertebrate biomass is confined in this layer (Adriano, 2001). In agricultural and grassland soils, this active biological zone corresponds to the plow layer or to the layer where roots are most dense. For soils where phreatophytic (groundwater-using) species are grown, the rhizospheric zone increases, because of the bigger root exploration volume down the soil profile; as a result changes in TEs availability can occur. The introduction of active roots in anoxic sediments can influence oxidation and drying through increasing

evaporation and aeration of the root zone, and the availability of some TEs such as Cd, Cu, and Zn (Vervaeke *et al.*, 2004).

Plant roots can play a vital role in the transformation and chemical speciation of TEs in soils (Koo *et al.*, 2005). Three mechanisms can be influenced by plant roots: modification of the soil environment in the rhizosphere, transformation of chemical form of TEs, and biosorption. Roots exude plant metabolites including several forms of carbohydrates and organic acids that can serve as energy source for soil microbes. These low-molecular-weight organic acids can complex metal ions rendering them potentially more mobile and bioavailable. Soil microbes can carry out important biotic redox reactions for some TEs in soils (Mahimairaja *et al.*, 2005). This includes the transformations of multivalence anionic TEs, such as As, Cr, and Se, altering their oxidation state and chemical species. For example, *Alcaligenes faecalis* was found to oxidize $As_{(III)}$ to $As_{(V)}$ (Osborne and Ehrlich, 1976). Bacteria, fungi, and algae could also reduce $As_{(V)}$ to $As_{(III)}$ (Frankenberger and Losi, 1995).

Soil microbes and invertebrates can promote temporary immobilization of metal ions by biological accumulation. Such accumulation is facilitated by biosorption by microbial biomass and its byproducts and physiological uptake by organisms through metabolically active and passive processes (Mahimairaja *et al.*, 2005). Microbes can dissolve minerals by direct or indirect action under aerobic and anaerobic conditions (Kurek, 2002). When oxidized metal compounds, such as $Fe_{(III)}$, $Mn_{(IV)}$, or $As_{(V)}$, act as terminal electron acceptors, anaerobic respiration becomes an example of direct dissolving action under anaerobic conditions. Oxidation of ferrous Fe or sulfur entities of metal sulfides to obtain energy is an example of direct dissolving action under aerobic conditions. Indirect dissolution of minerals can be the result of microbial activity connected with the production of organic and inorganic acids, and oxidizing agents which can influence soil conditions including changes in pH and Eh. Metals can also be mobilized from minerals by complexation with biomolecules of microbial metabolites. Organisms have developed two major strategies of internal sequestration of TEs: formation of inclusion bodies for instance in vacuoles (Clemens *et al.*, 1999) and binding of metals to heat-stable proteins, such as phytochelatins and metallothioneins, and stable molecules such as ferrihydrite (Hall, 2002; Hansel and Fendorf, 2001).

C. *In Situ* Stabilization

In situ stabilization, also coined "inert inactivation," aims to modify the mobility and bioavailability of a chemical pollutant to reduce its potential risk and thus transform a toxic pollutant to a contaminant which is still

present in the matrix but unable to reach or intoxicate the target organisms (Adriano *et al.*, 2004; Berti and Ryan, 2003). This is practically a remediation process to sequester metal contaminants in soil, accomplished by adding soil amendments to precipitate and/or sorb the metals in question, thus the term "inert inactivation." In this approach, the total metal content is not altered but the solubility and mobility are drastically reduced. The most studied and demonstrated amendment materials to induce metal stabilization include phosphate, Fe, and Mn oxide, and alkaline, stabilized biosolids (Adriano *et al.*, 2004). The mechanisms of this stabilization have not been conclusively established, but many processes can decrease metal mobility by, for example, increasing the CEC, or inducing precipitation of hydroxides or carbonates, or TEs migration into micropores.

Because hydroxyapatite is an abundant and inexpensive natural mineral, it has been used and promoted to inactivate metals, especially Pb as metal pyromorphite, a fairly stable precipitate over a wide range of pH (Ma *et al.*, 1993, 1994). It has also been used to stabilize Zn, Cd, and other trace metals in soils (Chlopecka and Adriano, 1996). The abundance and reactive nature of metal (Fe, Mn, and Al) oxides with most TEs in most soils enhance their use as metal inactivators. Commercial by-products, such as the "steel shot" or zero valence Fe, could be used in soil remediation for both cationic and anionic TEs such as As (Mahimairaja *et al.*, 2005) because once applied into the soils, the metallic Fe is oxidized and becomes more reactive. The heterogeneous and variable chemical nature of organic matter, more specifically biosolids, renders its use as a metal inactivator somewhat tenuous. Although the use of alkaline, stabilized biosolids has proven effective in immobilizing metal ions via adsorption, the capacity of DOM to complex and mobilize most metal ions renders it much less interesting to use in sequestering metals. This evolves around the possibility of advanced oxidation/transformation of organic matter, further complicating its role as an inactivator.

A nice example of *in situ* stabilization is the work done in Joplin, Missouri where Pb-contaminated soils in an urban area were amended with various phosphate treatments, which significantly reduced Pb transfer to plants, and even decreased its gastrointestinal availability in experimental animals (Berti and Ryan, 2003; Ryan *et al.*, 2004). These field trials and live animal tests, clearly demonstrated this technique's remediation potential.

In situ stabilization is a clear case of solubility–precipitation phenomena in soils where a process is induced by introducing foreign materials into the soils to foster high K_d. In essence, *in situ* stabilization induces attenuation of metals rendering them less threatening to the environment and biota. Since the inactivator materials are rather abundant, some found in nature, and inexpensive, they can offer a viable cost-effective remediation strategy for heavily metal-contaminated sites. However, data demonstrating their long term efficacy under field conditions are still lacking.

III. TRACE ELEMENT TRANSPORT PATHWAYS

The major mechanisms and transport vectors and pathways of TEs in terrestrial systems are exhibited in Fig. 4. Although the surface soil is emphasized in Fig. 4, most of the reactions are valid in the rest of the soil profile and the vadose zone as well. Atmospheric deposition, fertilizer applications, and soil amendments represent the major input sources into the soil. In pristine natural environments, aerial deposition is the most important source especially for TEs such as Hg, Pb, and As. Erosion is considered a very important pathway in arable lands, derelict mining sites, and other nonvegetated landscapes. The usual vertical transport pathway (i.e., mass flow and diffusion) can be complimented by preferential flow in macroporous and/or

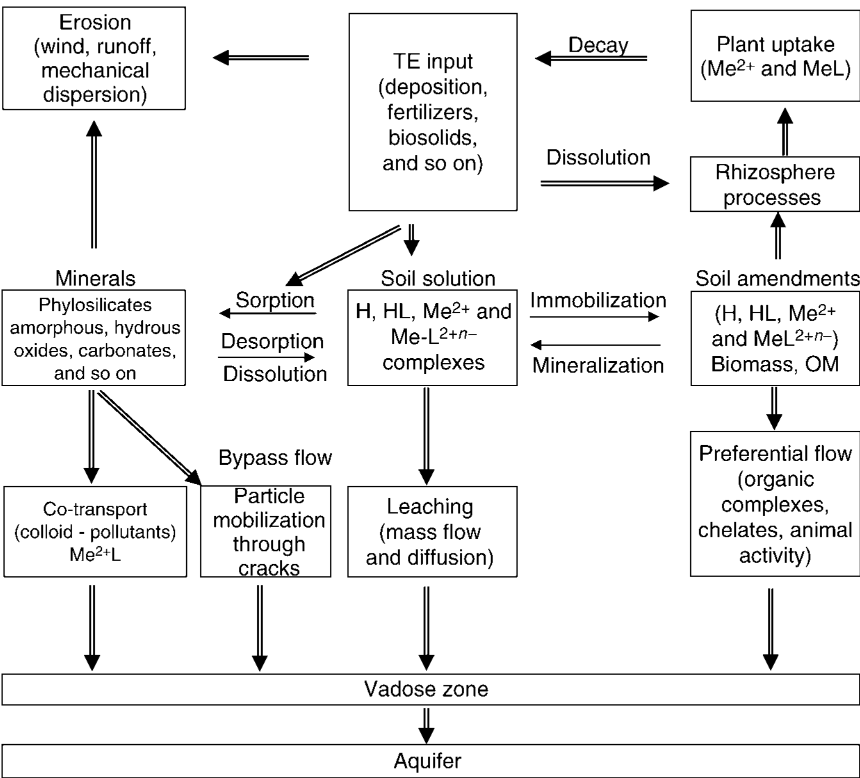


Figure 4 Possible mechanisms and pathways of trace element movement in soils. Me represents trace element ion or atom, H hydrogen ion or atom, L ligand or other substance that combines with Me.

cracked soils and facilitated transport due to TEs mobilization with colloids. Volatilization, as discussed in the text, is not included in Fig. 4, as it is usually more important in aquatic systems and applies to only certain elements.

Figure 4 presents an overview of possible mechanisms of TE movement in soils. Significant TE movement in soils after sewage sludge or wastewater application, or residues deposition has been observed (Lund *et al.*, 1976). Dispersion of these elements above the soil surface could be caused by soil erosion or by limited volatilization in the case for Se and Hg. While TE distribution in the top soil layer (0.3 m) can result from tillage operations, the vertical movement below this depth is likely due to other mechanisms. Although TEs movement in sewage-amended soils has been explained as a result of pH reduction caused by organic compounds (Robertson *et al.*, 1982), element transport has been observed even after an increase in pH. Transport of soluble chelate complexes with organic matter has been suggested as a possible explanation (Darmony *et al.*, 1983). Application of sewage sludge or C-rich residues can increase DOM (dissolved organic matter), promoting the formation of soluble TE-organic complexes, which can then reduce metal adsorption. Trace element movement in structured soils, through desiccation cracks, has been reported to be likely enhanced by preferential flow (Richards *et al.*, 1998). Movement of TEs from the application or deposition zone downward through the soil profile could occur by: (1) diffusion (either as free ions or as complexes), (2) movement of metal-laden particulates through soil macropores, (3) movement through soil cracks during the wetting–drying cycle, and (4) bioturbation (i.e., mixing by soil fauna) (Dowdy and Volk, 1983).

TE mobility depends on the soil particle distribution. Mobility is lower in fine textured soils as compared with coarse textured soils. While the flow rate affected the mobility of some TEs such as Be, Cr, and Fe, it had little effect on the mobility of Cd, Ni, and Zn at low concentrations (<97 mg liter^{-1}) in repacked soil columns. Leaching of these elements was in direct proportion to their concentrations (Alesii *et al.*, 1980). The slow water movement through soil columns apparently allowed the element adsorption onto soil surfaces, because TEs could diffuse into the soil aggregates where is a higher chance of adsorption. In addition, other adsorption processes, such as physical exclusion (molecules of TEs are unable to penetrate the inner layer of the minerals) or competitive sorption between target cations and cations present in the system, can affect TE transport in the soil.

While more than one transport mechanism is often simultaneously involved, the contribution of each mechanism varies depending on metal properties (Tam and Wong, 1996), soil conditions, and soil management (Murray *et al.*, 2004).

A. Diffusion and Dispersion

Diffusion is a transport mechanism that is active when a chemical moves between two locations, with the direction dependent on the concentration gradient. The random motion of chemical molecules is called molecular diffusion while the random motion of water containing dissolved chemicals is the turbulent diffusion (Hemond and Fechnor, 1994). This random molecular motion of molecules is called diffusive transport, contrary to the dispersive transport that is caused by the uneven distribution of velocities within and between various soil pores. Both these transport processes are described by Fick's law. The distance traveled by a solute during a particular time interval due to the Fickian transport is often much shorter than the distance traveled due to the mass flow. Krishna and Wesseling (1997) argued that the Maxwell Stefan formulation provides a better description of diffusion of trace metals than Fick's law. Diffusion of TEs is apparently relatively low in soils, with a possible exception of sandy acid soils that typically have low-adsorption capacities (Delolme *et al.*, 2004).

The dispersivity of a solute in a porous medium is defined as the increase of the spatial variance of its distribution with distance traveled (Rose, 1973). The dispersivity of elements such as Cd is much greater than that of nonreactive solutes due to the high rate of adsorption and due to the heterogeneous distribution of adsorption sites along pores (Gerritse, 1996). Different metal concentrations inside and outside of soil aggregates have been observed, apparently due to adsorption effecting the metal diffusion (Wilcke *et al.*, 1999). However, this local heterogeneity apparently also depends on the metal solubility, since Pb and Cu were observed to be lower in aggregate interiors than exteriors, but only small or no differences were observed for Cd concentrations.

In structured soils, metals can move with sludge-borne particles or colloids. Although metals have been detected in higher concentrations on ped surfaces, the binding of metals to water soluble organic ligands of the sludge may, apparently, depress metal adsorption on the clay-rich ped surfaces (Chubin and Street, 1981) and allow metal redistribution within the ped (Dowdy *et al.*, 1991). Therefore, the release of colloids is a diffusion-limited process (Schelde *et al.*, 2002) (see also Section II.A).

B. Preferential Flow

Movement of heavy metals with flowing water requires that TEs are in the soluble phase or associated with mobile particulates. The naturally occurring soil structure contains pores of different diameters, cracks formed by soil shrinking during drying and wetting cycles, and various macropores and

conduits created by soil fauna and plant roots. Liquid, suspended mobile colloids, and suspended particles can move vertically down the soil profile through these channels or cracks without interacting with the soil matrix. This preferential/nonequilibrium flow and transport is a recognized way for mobilizing contaminants in macroporous soils (Camobreco *et al.*, 1996; McCarthy and Zachara, 1989).

Since macropores in structured soils can conduct water rapidly to deeper soil horizons, while bypassing the denser, less permeable soil matrix (Jarvis *et al.*, 1999), an application of polluted residues with TEs during the dry season can cause rapid contaminant (pollutant) transport. Mineral surfaces in preferential pathways and matrix are often quite different, being coated in the flow paths with organic matter (OM) that can sorb specifically TEs (Bundt *et al.*, 2001). It has been proposed that TEs move down the soil profile through these preferential flow pathways after application of sewage sludge, waste water, or smelter residues. Sterckeman *et al.* (2000) reported that concentrations of Cd, Pb, and Zn increased down to a 2-m depth in soils near smelters. They suggested that earthworm galleries were the main pathways for accelerated particulate metal migration.

Soils receiving heavy sludge applications during a period of 15 years showed considerably increased concentrations of Hg and Cu below the application site (McBride *et al.*, 1997a). The authors suggested that downward transport via organic complexes and preferential flow are the main factors responsible for the increased element mobility (see also discussion on Fig. 4 of this section). Maeda and Bergström (2000) found that Zn leaching was enhanced by preferential flow, while Cu transport was negligible. Apparently, only insignificant interactions between the solid phase and metals in the soil solution occur when the soil structure and/or incoming water allow for preferential flow. Consequently, metals can move to much greater depths.

Preferential flow mechanisms in structured soils have been studied at both field and laboratory conditions. However, laboratory studies have several limitations due to difficulties in excavating and transporting undisturbed soil samples to the lab (Morris and Mooney, 2004). One of the difficulties of soil column studies is that the process of packing the column tends to destroy or reduce soil aggregation and the resulting exposure of much greater surfaces on the soil solids increases tremendously the potential for sorption onto the solid phase. In addition, the type of experimental method used for studying the preferential flow processes at the laboratory scale can also influence the TE transport. However, more attention should be given to studying these processes since Flury *et al.* (1994) reported that the majority of water flow can use less than 10% of the pore space and move preferentially much faster and to much greater depths than uniform flow.

C. Colloidal Transport

Trace elements generally have high affinity for sorbing substances, which are mainly associated with the solid phase, and thus the amount in the soil solution is relatively small (see also Section II.A). Colloidal particles can act as TEs carriers, since they are highly reactive, have low bulk density, are lighter than water, and can thus be easily suspended (Totsche and Kügel-Knabner, 2004). The activities of Mn, Co, Sb, Cs, Ce, and Cu in groundwater samples collected from underground nuclear test cavities at the Nevada Test Site were associated with colloidal particles (Buddemeier and Hunt, 1988). Zhang *et al.* (2003) observed TEs were transported to surface water through runoff attached in the fine fractions: the <53-μm fractions contained 13–19% and the 0.125- to 0.053-mm fraction contained 28–38% of the total Cu, Cd, Cr, Co, Pb, Ni, and Zn. Oxyanions of eluted Cr and As were associated mainly with Fe and Mn oxides (Sandhu and Mills, 1987). Also As-organic compounds complexes have a neutral charge and move faster than the dissolved anionic arsenate (Kaplan *et al.*, 1993). Grolimund *et al.* (1996) observed the movement of Pb bound to colloids and concluded that colloid-facilitated transport is an important process especially for strongly sorbing contaminants. They also noted that colloid-facilitated transport is a very complex process since the release of colloid-carrying contaminants is kinetically limited, and thus the flow rate significantly affects the transport.

Application of certain organic residues to structured soils could cause movement of TEs by particulate transport. In soils with undisturbed structure, macropores can act as rapid flow conduits and particulates and contaminants associated with organic (particulate) matter can move rapidly through them to subsurface soil layers (Oygarden *et al.*, 1997). Keller *et al.* (2002) found in a lysimeter experiment that particulate matter in drainage water accounted for, on average, 20% of trace metals leaching from a sludge-amended soil.

The role of colloids in facilitating the TEs transport is moderated by the element and colloid type, by concentration of the TE, and by soil properties. It has been observed that the increase in the colloid surface area, the charge of the colloids, pH, and the organic compounds in solution can facilitate transport of colloids and TEs. In contrast, TEs associated with large colloids have lower movement. Also the increase in the element concentration affects coagulation, flocculation, flow retardation, and pore clogging (Karathanasis, 1999) through cation–colloid association, which then decrease solubility. Apparently, the solid phase dispersion increases at the low ionic strength and thus the colloid migration is more likely to occur (Schelde *et al.*, 2002). For example, Zn will move faster in the leachate from an acidic sandy soil column when the column is leached with deionized water than when leached

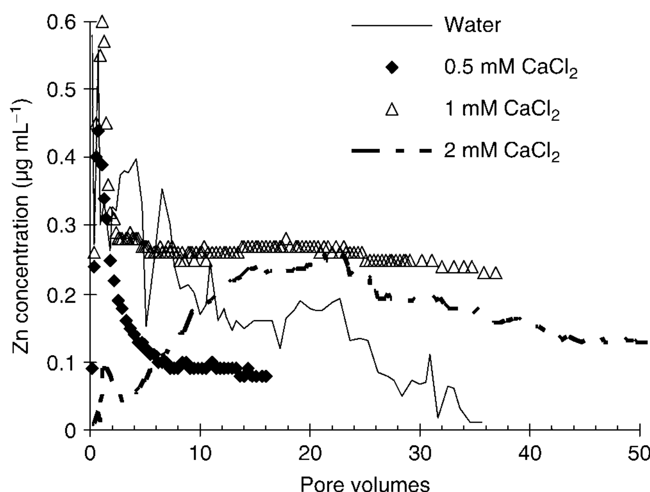


Figure 5 Zn breakthrough after leaching soil columns with deionized water, and 0.5 or 2 mM $CaCl_2$ solutions through an acid sandy soil (Carrillo-González, 2000).

with 0.5 or 2 mM $CaCl_2$ solutions and this is believed to be due to dispersion of organic colloids (Fig. 5) (Carrillo-Gonzalez, 2000).

The adsorption of dissolved organic molecules and humic substances can modify the surface charge of colloids, increasing their stability and mobility. For example, colloids composed of oxides, layer silicates, and calcium carbonate and those coated with humic substances can develop a negative charge and remain in the solution (Harter and Naidu, 1995). Adsorption of some organic compounds is partially irreversible (Weigand and Totsche, 1998), which affects the specific surface, and therefore could modify the retention of TEs. For instance Fe and Zn adsorption decreased with the presence of natural organic matter at pH 5, but changes were also observed at pH 7 (Schmitt *et al.*, 2002).

D. Soluble Metal Complexes

Organic compounds in the soil that may form complexes with metal ions may be grouped into three main classes (Senesi, 1992): (1) naturally occurring molecules derived from soil biota and having known structure and chemical properties (polysaccharides, amino acids, polyphenols, and aliphatic acids), (2) xenobiotic organic chemicals derived from human, agricultural, industrial and urban activities, and (3) humic substances that include

humic and fulvic acids, and humin. Fulvic acids represent a significant proportion of organic carbon. They form complexes that bind TEs (e.g., Cu, Fe, Cd, Zn, V, and Ni) mainly on carboxylic and phenolic functional groups (Saar and Weber, 1982) and on organic molecules derived from chemicals used in agriculture, industrial activities, and urban residues.

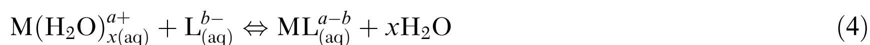
Cations tend to form stable complexes with organic ligands (see also Section II.A). DOM forms stronger complexes with Cu and Cd than those formed with Pb and Zn. More than 50% of Cd was bound in the organic matter (Karapanagiotis *et al.*, 1991), and specifically humic and fulvic acids derived from sludge play a significant role in the chemical speciation of metals. Senesi *et al.* (1989) suggested that the humic acid fraction of sludge-amended soil shows selectivity in binding trace metal ions (Cu^{2+}, Fe^{2+}, Ni^{2+}, Zn^{2+}, Cr^{6+}), whereas more labile metal ions are desorbed and replaced (Mn^{2+}, V, Ti, Mo).

It is expected that xenobiotic organic molecules discussed earlier could also form complexes with metals. For example, the following chelating ligands can be found in wastes (sewage sludge and wastewater): nitrilotriacetate (NTA), hydroxyethyliminodiacetate (HIDA), dihydroxyethyl glycine (DHG), triethanolamine (TEA), hydroxyethylenthylen diaminotriacetic acid (HEDTA), diethylenetriaminepentaacetic acid (DTPA), CDTA (*trans*-1,2-cyclohexyl-diamine-*N,N,N′,N′*tetraacetate), ethylene-bis-oxyethylenenitrilo-tetraacetate (EDDHA), HBED (*N,N*-bis (2-hydroxybenzyl) ethylenediamine-*N*-*N′*-diacetate), oxalic acid, gluconic acid, and citric acid (Lasat, 2002; Martell, 1975; Russel *et al.*, 1998). These substances have been detected in rivers (Hoffman *et al.*, 1981) and the vadose zone (Jardine *et al.*, 1989). It has been observed that trace metals, such as Cd, Cu, and Pb, were associated with low and intermediate (1000–10,000) molecular weight organics, which passed through 0.4-μm membrane filters.

Element–ligand (organic) formation from hydrated elements can be represented as follows:



$$M^{a+}_{(aq)} + xH_2O \Leftrightarrow M(H_2O)^{a+}_{x(aq)} \tag{3}$$



$$M(H_2O)^{a+}_{x(aq)} + L^{b-}_{(aq)} \Leftrightarrow ML^{a-b}_{(aq)} + xH_2O \tag{4}$$

where M is the trace element ion and L is the ligand; the number of trace elements and ligands could change depending on the chemistry of both reactants.

The stability of these complexes depends on the equilibrium constants, which provide an indication of the affinity of the ion for ligand, and for bi- and polydentate ligands. Each successive interaction has its own equilibrium constant and the product of successive values gives the net stability constant. The successive interactions depend on the association of the ligand and the H^+

$$\beta_i = \frac{[\mathrm{ML}]}{[\mathrm{L}^{b-}] \cdot [\mathrm{M}(\mathrm{H_2O})_x^{a+}]} \tag{5}$$

where β is the stability constant for the *i* association.

The conditional stability constants for TEs and fulvic acid vary widely as a function of the nature of the original organic matter, from which fulvic acids are derived, and pH (apparently increasing with pH). Stability constants for TE–organic acid complexes increase with the molecular weight. Chelating ligands form very stable associations with TEs and are able to extract them even if they are bound to the organic matter. This increases the likelihood of TE migration from the deposition site if synthetic organic ligands, such as ethylenediamine tetracetic acid (EDTA) or NTA, are present in the applied residues.

Strong ligands, such as EDTA, show almost no adsorption on the soil surface and have been reported to increase TEs concentration in the soil profile (Kent *et al.*, 2002). In addition, they may exhibit a low rate of degradation, and thus could modify the behavior of TEs. For example, Wu *et al.* (2003) showed that a significant increase in Cu and Pb mobility (but not Zn and Cd) was achieved when a polluted paddy soil was leached with EDTA. While Ni and Zn were displaced with the EDTA solution from a quartz sand aquifer, Al and Fe dissolved from the sediments competed with Zn and Cd to form metal–EDTA complexes (Kent *et al.*, 2002). Apparently, there is a competition among metal ions during leaching with the EDTA solution. Cu was leached slightly faster than Zn and Cd, while Pb moved even slower. However, the rate of mobility of Pb increased after more mobile elements were displaced (Sun *et al.*, 2001). The vertical movement of Cu, Ni, and Zn in calcareous soils in the form of mobile metal organic complexes in the soil solution was also reported by Kaschl *et al.* (2002).

Novillo *et al.* (2002) observed that Zn applied in solution to the top of the soil column and leached with dissolved organic ligands, migrates at different rates in acid, neutral, and calcareous soils. The retention of TEs depends on the type of metal complexes formed. Zn–EDTA complexes are very stable and can migrate to larger distances than other complexes such as Zn-lignosulfonate or 2-hydroxyl-1,2,3 propanotricarboxylate. The addition of EDTA, citric or oxalic acids increased Cr mobility more than 200-fold (Shahandeh and Hossner, 2000).

E. Leaching and Runoff

Leaching of TEs from soils has resulted from intensified use of fungicides, application of sewage sludge, spilling timber treatment solution, and acid mine wastes. There are contrasting reports about leaching of TEs from

fertilized soils. While some authors found negligible movement of TEs (Singh and Myhr, 1997), others reported substantial losses (Williams and David, 1976). Transport is likely to occur in acid, sandy soils, where the adsorption process is relatively insignificant, and where the water fluxes vary from moderate to high (the hydraulic conductivity ranges from 3 to >300 mm h^{-1}). It may also occur in subsoil (below the 0.3-m depth) where organic matter content and metal retention decreases. The probability of movement of TEs also increases with their concentration. Migration of TEs may take place when their concentrations exceed the capacity of the soil to retain them, that is, especially in stabilized soils. The metal loss from application sites is usually low, but varies significantly among elements.

Leaching is strongly affected by soil pH (see also Section IV.A). While low-metal leachability at high-pH values is the norm, potential leaching from dredged sediments at pH 4 has been estimated to be as high as 61% for Zn, 60% for Cd, 53% for Mn, 27% for Co, 26% for Ni, 14% for As, 4% for Cu, and 2% for Pb (Singh *et al.*, 2000). Formation of ion-pairs with inorganic anion can also increase mobility. Doner (1978) was the first to suggest that an anion index of the leaching solution could play an important role in the displacement of TEs in sandy soils. He observed that Cd moved four times faster when Cl^- was present in the solution instead of ClO_4^-.

TEs can be leached in the soil profile as hydrated cations, oxyanions, and organic or inorganic complexes. Darmony *et al.* (1983) took soil samples to a depth of 150 cm (in 25-cm increments) from a sludge-treated silt loam soil and observed that Zn was translocated to the 75-cm depth, with a gradual decline in concentration with depth. They concluded that the transfer of soil in desiccation cracks accounted for the metal distribution. Giusquiani *et al.* (1992) leached soil columns amended with fresh compost (90 t ha^{-1}) with 0.01 M $CaCl_2$ and observed that the total concentration of complexed TEs increased significantly in the organic matter that passed through the soil column. Fraction of leached metals from a sludge amended soils (sand and sandy loam) ranged from 10% to 41%, 1.8% to 25%, 21% to 51%, and 6.8% to 41% for Zn, Cu, Pb, and Ni, respectively. No differences were observed between dry or fresh sludge applications (Gove *et al.*, 2001). Legret *et al.* (1988) observed an increase in exchangeable Cd and Pb in deep layers (0.4–0.6 m) of the sandy soil profiles after application of sewage sludge. Apparently, cations in solution can displace exchangeable Cd and Pb from the upper layers and move down. They concluded that exchangeable forms of TEs can play an important role under certain soil conditions. Also, the dominant anion in the solution has an important effect on the element leaching apparently due to two processes: (1) soluble metal-ligand formation, which can increase TEs in solution, and (2) ligand adsorption, which can modify surface adsorption and aggregation behavior of the particles.

Some TEs can move in the soil profile not only as hydrated cations, but as inorganic complexes. For instance, Zn can form with Cl^- the following complexes depending on chloride concentration and pH of the solution: $ZnCl^+$, $ZnCl_2^0$, $ZnCl_3^-$, and $ZnCl_4^{2-}$. Theoretically, elements with high values of the stability constant, such as Cd and Hg chloride complexes, are more stables in the solution and are more likely to migrate. However, the retention of these complexes on the soil surfaces can affect their mobility.

Soil erosion and surface water runoff are other mechanisms that can mobilize TEs in different environments. These mechanisms of TE dispersion are considered to be diffuse pollution because most of the suspended sediments carried with water during heavy rainfalls have a low density and can remain suspended. Barrel *et al.* (1993) reported that runoff from selected highways contained about 45–798 mg $liter^{-1}$ of suspended solids, 0.073–1.78 mg $liter^{-1}$ of Pb, and 0.113–0.998 mg $liter^{-1}$ of P. Cr, Fe, Mn, Cu, Ni, Pb, and Cd have also been detected in street and highway sediments (Barbosa and Hvitved-Jacobsen, 1999; Rietzler *et al.*, 2001). The highest concentrations were detected during the first rainfalls after the dry season (Jiries *et al.*, 2001) and they varied depending on the nature of the element. While concentrations of Fe and Cu increased as the water flow increased, Zn, Cr, and Mn concentrations decreased. The dilution effect due to the input of sediments with low concentrations of these elements and the presence of iron oxides apparently caused the displacement among these TEs (Carvalho *et al.*, 1999).

Increases of TE concentrations in runoff from agricultural soils, after repeated pesticide applications, has been reported (Moore *et al.*, 1998; Quilbé *et al.*, 2004). However, He *et al.* (2004) found that dissolved TE concentrations in runoff from vegetable and citrus fields were usually below drinking water standards and that the TE concentrations were affected by soils TE accumulation, rainfall intensity, volume of runoff, soil properties and agricultural practices.

Release of metals from abandoned mining areas can occur due to acid mine drainage and erosion of waste dumps and tailing deposits. Presence or absence of vegetation, topographical characteristics and rainfall patterns can strongly affect the erosion processes (Clark *et al.*, 2001; Lee *et al.*, 2001). Birch *et al.* (2001) linked metal contents (easily exchangeable phase) in fluvial sediments to the coal mining activities. Ongley *et al.* (2003) observed high concentrations (from 10 to 100 mg kg^{-1}) of As, Cu, Pb, and Zn as far as 6 km away from piles of mining residues containing high concentrations of As (32,000 mg kg^{-1}), Pb (41,000 mg kg^{-1}), and Zn (17,000 mg kg^{-1}). Heavy rainfall storms during short time intervals after long dry seasons were the main cause for the elevated metal concentrations. Fine clay minerals contribute to TE migration because of the observed close relationship between some elements, such as Hg in sediments and Al from silicates, and other

biogeochemical parameters related to aluminosilicates (Roulet *et al.*, 2000). These sediments contribute to soil, water, and sediment pollution that can eventually modify the biogeochemical cycles.

F. Volatilization

Volatilization of certain TEs occurs through microbial transformation of metals/metalloids to their respective metallic, hydride, or methylated form. These forms have low-boiling points and/or high-vapor pressure, hence are subject to volatilization. Methylation is considered to be the major process of volatilizing As, Hg, and Se in soils and sediments, resulting in the release of poisonous methyl gas such as alkylarsines (Frankenberger and Benson, 1994; Wood, 1974). Arsenic forms volatilized from soil or water are $AS_{(III)}$ and $AS_{(V)}$, di- and trimethylarsine. However, these two alkylarsines could be adsorbed onto iron oxides. Most scientists accept that Hg volatilization requires three steps: reduction of $Hg_{(II)}$ to $Hg_{(0)}$, diffusion or mass transport of $Hg_{(0)}$ to the soil surface and then transport to the atmosphere by diffusion or mass flow (Bizily *et al.*, 2002; Grigal, 2002). Hg reduction may involve abiotic processes, but there is also an enzymatic reduction of bivalent ions to the elemental form which are subsequently volatilized (Essa *et al.*, 2002). The concentration of Hg volatilized from soil could lead to air concentrations ranging from 1.5 to 3.7 ng m^{-3} (Kim *et al.*, 1995). Similarly to arsenic, selenium can be oxidized and then transformed by microorganisms to dimethyl-selenide a volatile compound. Soil organic matter can also contribute to enhance Se volatilization.

Volatilization through methylation is thought to be a protective mechanism, that is, a detoxification process used by organisms such as microorganisms in seleniferous environments (Frankenberger and Losi, 1995). Volatilization is affected by soil pH, OM and iron oxides content, temperature, and colloids content (Grigal, 2002). Thus the loss of TEs in gaseous form from the soil is basically limited to those that can be biologically methylated such as As and Se, and to $Hg_{(0)}$.

IV. FACTORS AFFECTING TRACE ELEMENT MOBILITY AND TRANSPORT

TE mobility in soils depends on their interactions between the solid and liquid phases, which determine their partitioning. The underlying mechanisms regulating the partitioning of these TEs include physicochemical and biological processes (discussed in Section II), which in turn are controlled by

several factors. As discussed earlier TE solubility and partitioning between the solid and liquid phases is the starting point for understanding their fate and transport in soils (Adriano, 2001; McBride, 1989; Ross, 1994).

A. Soil pH

It is generally viewed that pH is the main variable controlling the solubility (see also Section II.A.1), mobility and transport of TEs, as it controls metal hydroxide, carbonate and phosphate solubility. Soil solution pH also affects ion pair and complex formation, surface charge, and organic matter solubility (Appel and Ma, 2001; Huang *et al.*, 2005; Lebourg *et al.*, 1998).

TE solubility could be strongly affected by small changes in pH values. Metal solubility and their ion activity decrease with higher pH. The release of TE from freshwater sediments after gradual reduction of pH was Ca $\cong$ Mn >Fe > Ni > Zn > Cd > Al > Pb > Cu, which depend on the solid compound that held the TEs (Buyks *et al.*, 2002). Soil pH controls the movement of TEs from one soil compartment to another, since TEs can be held in the lattice of secondary minerals (1:1 and 2:1 clay minerals), adsorbed on Fe and Mn oxides, and carbonates, or precipitated as carbonates. For instance, Maskall and Thornton (1998) found increases in the proportion of readily mobile form of Pb and Zn as pH fell below 5. Cattlet *et al.* (2002) observed a decrease of the Zn^{2+} activity in the soil solution as pH increased. They concluded that the organic matter adsorption and the formation of franklinite accounted for this trend.

Soil pH affects many soil processes including TE sorption. Boekhold *et al.* (1993) observed that Cd sorption doubled for each 0.5 increase in pH from 3.8 to 4.9. In sandy soils, a unit increase in pH produced a 2- to 10-fold increase in ion sorption. The type and concentration of electrolyte and the substrate control this change (Barrow and Whelan, 1998; Harter and Naidu, 2001). Nickel removal from the soil solution by pyrophyllite increased strongly when pH went from 6 to 7.5, or even higher (Scheidegger *et al.*, 1996). While the retention and release varied little for various cationic elements, they manifested large differences for those TEs that form anionic chemical species such as As, Cr, or Se. The concentration of arsenate in solution, that is, the predominant inorganic species of As decreased at low pH because of its adsorption (Manning and Goldberg, 1996). Tyler and Olsson (2001) observed an increase in the concentrations of As, Se, Mo, Cr, Sb, and U in soil solutions with increasing pH.

A direct relation has been found between Cu, Zn, Cd, and Pb activities ($pM = -\log M_T$) and pH, organic matter content, and total metal content (M_T), resulting in a general equation $pM = a + b\ pH - c \log (M_T\ OM^{-1})$ (McBride *et al.*, 1997b). Likewise the variation of Cd leached from allophanic

soils can be explained by a regression model involving, as independent variables, leachate pH and total drainage (Gray *et al.*, 2003).

$$\mathrm{Cd_{leached}}(\mathrm{g\ ha^{-1}}) = 3.5 - 0.591\ \mathrm{pH_{(leachate)}} + 0.003\ \text{total drainage (mL)} \quad (6)$$

While the solubility of naturally occurring Cd and Zn from mineral soils depends upon pH, in some situations dissolved concentrations of Cd, Cu, and other elements, such as Pb, may not follow a single relationship with pH for polluted soils. In some cases we can even observe that the concentration of dissolved metal is better predicted simply as a function of total soil metal burden (Sauvé *et al.*, 1997b for Cu).

Radiolabile Cd and Zn in topsoils, extracted with 0.01 M $CaCl_2$, increased as the soil pH decreased (Adams and Sanders, 1985; Degryse *et al.*, 2003). High proportions of metal ions in the soil solution is unlikely to occur at pH values higher than 6.5 (Plant and Raiswell, 1983), because the predominant form is hydroxo-complexes. However, the soluble Pb hydroxo-complexes may contribute poorly (about 12%) to the total dissolved Pb (Lindsay, 1979). The apparently large TE retention at pH values larger than 6 is partially due to ionization of surface OH and COOH groups, which involves complex formation on high-selectivity sites (Abd-Elfattah and Wada, 1981).

Still, as a general model, useful empirical regressions can be used to predict concentration of trace metals in soil solution. One possible model is given as Eq. (7):

$$\begin{aligned}\mathrm{Log_{10}}(\text{dissolved metal}) = a + b\ \mathrm{pH} + c\ \mathrm{Log10}(\text{total soil metal}) \\ + d(\text{soil organic matter})\end{aligned} \quad (7)$$

Coefficients for those regressions or similar ones are available from various reviews (Sauvé, 2002; Sauvé *et al.*, 2000a, Tipping *et al.*, 2003). Albeit soil organic matter is often a significant parameter (except for Pb), most of the variability is usually explained by soil pH and total metal content.

B. Chemical Speciation

Although the total TE content largely determines the extent of elemental partitioning between the aqueous and solid phases in soils, the chemical speciation is likely one of the most important factors that influences TE availability, solubility, and mobility. TE ions can combine with organic and inorganic ligands or substances in soil solution or in the rhizosphere. The ligands can be hydroxyl, carbonates, sulfate, nitrate, chloride, DOM, or

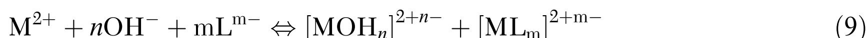
chelating agents. The distribution of metal ion species is apparently governed by redox reactions, pH, and solubility of hydroxides, carbonates, oxides, and sulfides. Three kinds of soluble complexes can be formed between metal ions and ligands: ion pairs, soluble metal–organic ligand complexes, and chelation (Gao *et al.*, 2003). While the first type is a weak electrostatic association, the second is a strong association that includes covalent bonding.

The proportion of free hydrated cations and OH complexes changes as the pH value changes:



$$M^{2+} + nOH^{-} \Leftrightarrow [MOH_n]^{2+n-} \quad (8)$$

where n can have values from 1 to n. The number of OH^- associated with M^{2+} increases as the OH^- concentration increases. Presence of $Pb(OH)^+$ and $Pb(OH)_2^0$ has been used to explain Pb extractability at high-pH values. When other anions are present in the solution such as Cl^-, NO_3^-, SO_4^{2-}, HCO_3^{2-}, or CO_3^{2-}, a new equilibrium takes place and more than one type of complexes is present:



$$M^{2+} + nOH^{-} + mL^{m-} \Leftrightarrow [MOH_n]^{2+n-} + [ML_m]^{2+m-} \quad (9)$$

Since some of them can form soluble complexes, a wide range of chemical species can be present in the solution at the same time depending on ion concentrations. Lebourg *et al.* (1998) found in seven soils from the Calais region in France that Pb^{2+} predominated at pH lower than 6.5, but carbonate complexes became important at higher pH. Zn^{2+} and Cd^{2+} were dominant forms of Zn and Cd at low pH, but the speciation was a function of pH. Ion pairs behave as monovalent ions and can be adsorbed on hydroxyl surface complexes (Gier and John, 2000).

The soluble nature of $CdCl^+$ complexes caused substantial leaching of Cd from a soil column (Doner, 1978), reduction of Cd adsorption on a montmorillonite (Hirsh *et al.*, 1989), and Cd bioavailability to plants in soils (McLaughlin and Tiller, 1994) (see also Section VI.B). $CdCl_2{}^0$, $CdCl_3{}^-$, or $CdCl_4{}^{2+}$ complexes could be formed at high-chlorine concentrations (Khalid, 1980), but are unlikely to occur at natural soil conditions.

TE mobility is strongly restricted by carbonates in calcareous soils, likely due to chemisorption or precipitation (Papadopoulos and Rowell, 1988). However, the presence of humic acids increases Cd, Co, Cu, and Zn adsorption even at low pH, while at high pH they reduced the precipitation of TEs, apparently due to the formation of metal humate species (Sparks *et al.*, 1997a,b).

The stability of the metal–organic matter complexes is affected by pH. Copper, Pb, and Cr form stable complexes, while Cu complexes dissociate at low pH. The association of TEs to ligands in the soil is controlled by pH, with the ligand species ionic concentration increasing with higher pH.

C. Soil Organic Matter

Organic matter (OM) can play a dual role in TEs solubility. Particulate OM, by virtue of its high CEC, can effectively adsorb TEs (Adriano, 2001). High-molecular-weight organic compounds can also bind and strip TEs from the solution, because they can be insoluble and therefore semi-immobile (Schmitt *et al.*, 2002; Sparks *et al.*, 1997a). It has been reported that humic acids can increase Cd retention on kaolinite four times (Taylor and Theng, 1995) and the formation of stable organo metallic complexes can lead to relatively lower mobility of Cu, Pb, Ni, Zn, and Cd (Karapanagiotis *et al.*, 1991).

It has also been observed that insoluble organic molecules decreased the availability of some elements, such as Cu or Pb, by the formation of insoluble complexes (Bataillard *et al.*, 2003; Sauvé *et al.*, 1998). In contrast, Temminghoff *et al.* (1998) found that humic acids enhanced Cu mobility, but the process was strongly affected by Ca concentration and pH of the soil solution. In general however, low-molecular-weight compounds, such as fulvic acids, could remain in the soil solution and thus increase the mobility of bound metals (Christensen *et al.*, 1996; Chubin and Street, 1981; Naidu and Harter, 1998). Some authors have found that the naturally occurring DOM can increase the mobility of some elements such as Cd (Dunnivant *et al.*, 1992; Lasat, 2002). OM may also limit the precipitation of chloropyromorphite [$Pb_5(PO_4)_3Cl$], because DOM inhibits crystal growth (Lang and Kaupenjohann, 2003). Also organic ligands could affect crystallization of secondary minerals; organic coatings around the crystal seeds may inhibit or retard crystallization (Holm *et al.*, 1996; Ma, 1996).

Christensen *et al.* (1996) concluded from sorption experiments with aquifer material that DOM present in landfill leachates formed soluble complexes with Cd, Ni, and Zn, which migrated at low speed (less than 1–2% of the water migration velocity). The contribution of DOM to Cd, Ni, and Zn migration in an aquifer is directly proportional to the complex formation constant and ligand concentration, and inversely proportional to the distribution coefficient on the aquifer suspension. OM reduced Zn, Pb, and Fe adsorption onto kaolinite and montmorillonite at pH 5 and 7, possibly due to metal-complexes formation (Schmitt *et al.*, 2002).

The adsorption of organic compounds on soil minerals and the interaction among organic molecules and TEs are affected by the soil pH. At low pH, cations compete with H^+ for the functional groups (Balcke *et al.*, 2002; Weigand and Totsche, 1998). The OM content also affects of TE complexes sorption (Carrillo-Gonzalez *et al.*, 2005). Because of the hydrophobic character of organic compounds, the solid phase with the high-OM content can adsorb more organic compounds than the soil with lower OM content; application of OM increased acidity (Strobel *et al.*, 2004). Strawn and

Sparks (2000) conducted Pb desorption experiments using stirred-flow reactors and observed that the amount of Pb desorbed decreased as the OM increased in the medium.

Preferential flow paths can adsorb certain TEs due to the higher OM content compared to the soil matrix (Bundt *et al.*, 2001). In contrast, the soluble OM may increase the amount of TEs in the soil solution by the formation of soluble organo metallic complexes (Naidu and Harter, 1998). It has been suggested that OM may limit the ability of phosphate to immobilize Pb (Lang and Kaupenjohann, 2003).

D. Fertilizers and Soil Amendments

Although fertilizers have been identified as a source of TEs (Adriano, 2001; Gimeno-Garcia *et al.*, 1996; Jeng and Singh, 1995), the amounts of TEs derived from fertilizers typically do not significantly increase TE uptake by plants. The main exception are possibly phosphate fertilizers. He *et al.* (2005) reported that phosphate rocks contain on average 11, 25, 188, 32, 10, and 239 mg kg^{-1} of As, Cd, Cr, Cu, Pb, and Zn, respectively. Cadmium is probably the main element of concern in this case since it can vary from near zero to more than 150 mg Cd kg^{-1} in some phosphate fertilizers (Mortvedt and Osborn, 1982). Cd is the most susceptible to be of concern in terms of crop accumulation from fertilizers and soil amendments (McLaughlin *et al.*, 1999).

Moreover, application of fertilizers can further affect soil properties related to metal availability. Ammoniacal nitrogen fertilization has been shown to decrease soil pH in the rhizosphere, which could modify TEs (Zn, Cu, and Mn) availability (Mench, 1998). In addition, formation of metal complexes with NH_3 could affect TE availability due to its high-stability constants for Cd, Co, Cu, Ni, and Zn (Ringbom, 1963).

Metal phosphate minerals (see also Section II.C) control metal solubility in the soil suspension and induce formation of metal phosphate precipitates. It has been observed that addition of hydroxyapatite decreased the solubility of Pb^{2+}, Ni^{2+}, Cd^{2+}, Co^{2+}, Sr^{2+}, or U (Seaman *et al.*, 2001). Soluble phosphate, a rock phosphate, fertilizers such as monoammonium phosphate and diammonium phosphate decrease Cd, Pb, and Zn mobility, probably due to formation of metal minerals (McGowen *et al.*, 2001) (see also Section VI.B). Also phosphatic clay minerals, which characteristically have a high content of apatite $[Ca_{10}(PO_4)_6(OH,F,Cl)_2]$, are effective metal adsorbents (Singh *et al.*, 2001). However, DOM present in the solution can coat the phosphate surfaces and thus inhibit the sorption on phosphate compounds, reducing the amount and rate at which phosphate becomes available for precipitation.

Application of limestone and alkaline waste by-products such as beringite, a modified aluminosilicate produced from the fluidized bed burning of coal refuse, to the soil has increased pH and precipitated metals, Beringite depresses TEs (Adriano *et al.*, 2004) mobility, apparently by precipitation, ion exchange and crystal growth. Zeolites have reduced TEs solubility by changing the soil pH and, to some extent, by binding metals to their surfaces (Mench *et al.*, 1998; Wingenfelder *et al.*, 2005). Synthetic zeolites tend to be more efficient than natural zeolites. Ferric hydrous oxide also is known to retard metal mobility (Kukier and Chaney, 2001).

Applications of OM and biosolids to soils increase DOC pool, which could form complexes with TEs; more than 90% of Cu, Zn, and Pb were complexed with DOC and mineral colloids (Al-Wabel *et al.*, 2002). Planquart *et al.* (1999) found migration of Cu and Pb within the profile as a result of the application of biosolids, probably due to the release of soluble organic compounds. However, although soluble TEs increased with long term application of biosolids, an increase in metal adsorption and hence decreased bioavailability has been reported due to enhanced adsorptive phase (Chubin and Street, 1981; Li *et al.*, 2001).

E. Redox Potential

Redox processes are controlled by the aqueous free electron activity (Sposito, 1983), but certain microorganisms can modify and mediate most redox reactions in aquatic and terrestrial environments (Motelica-Heino *et al.*, 2003). Several elements, such as As, Cr, Mn, Fe, V, Mo, and Se, manifest different oxidation states in the environment. Arsenic is found in −3, 0, +3, and +5 oxidation states. At the soil surface, oxidizing conditions are favored, so it allows the formation of either $As_{(V)}$ or $As_{(III)}$. However, microbial activity could promote methylation, demethylation, or change in the oxidation state, while the presence of clay minerals, Fe, Al, Mn oxides, and OM can also modify the oxidation state (O'Neill, 1995). The most stable As chemical species are H_3AsO_4 up to pH 2.2, $H_2AsO_4^-$ in the pH range approximately between 2 and 7, and $HAsO_4^{2-}$ above pH 7. It has been reported that more than 90% of the total As present in the soil was arsenate (Matera *et al.*, 2003). Furthermore, As was shown to move to groundwaters 180-m deep, being released from minerals such as adamite [$Zn_2(AsO_4)OH$], arsenopyrite (FeAsS), lolingite (Fe_2As), mimetite [$Pb_5(AsO_4)\cdot Cl$], olivinite [$Cu_2(AsO_4)OH$], hidalgoite [$PbAl_3(AsO_4)SO_4OH_6$], and tennantite [$(CuFe)_{12}As_4S_{13}$] (Armienta *et al.*, 1997).

Chromium, Hg, Se, and Mn occur in more than one oxidation state, with their solubility in the soil depending on pH and mineral content. $Cr_{(III)}$ is an essential nutrient, it has a low solubility, it is mainly trivalent, it is specifically

sorbed by Fe, Mn, and clay minerals, and its concentration in solution decreases with increasing pH and soil OM content (Bartlett and Kimble, 1976). $Cr_{(VI)}$ on the other hand is anionic, relatively soluble and represents a very mobile ion. Combined with its toxicity and carcinogenicity, this element certainly warrants careful speciation to differentiate trivalent from hexavalent chromium. The mobile and reactive chemical species of mercury are Hg^0, $(CH_3)_2Hg$. Hg^{2+} and HgX_n^{2+n-}, where X could be OH^-, Cl^-, Br^-, or organic ligands, hence more than one oxidation state could be present in the same environmental matrix. Selenate $Se_{(VI)}$ ($HSeO_4^-$) is the most mobile form of Se that can be leached to groundwaters. But, it is unlikely that selenate could migrate to deeper groundwaters underlying acid soils (Neal, 1995).

Manganese occurs in two oxidation states: $Mn_{(IV)}$, which is the most stable in neutral to slightly alkaline conditions, and $Mn_{(II)}$, which is stable in reducing conditions. The solubility of Mn is highly sensitive to redox conditions; under oxidizing conditions Mn is precipitated as nodules or concretions of Mn oxides, but reduction of Mn oxides increases Mn solubility (Sposito, 1989). TEs such as Cu, Co, Cr, Ni, Pb, and Zn associate to Mn oxides through coprecipitation and substitution (Green *et al.*, 2003; Liu *et al.*, 2002; Negra *et al.*, 2005), so when Mn is reduced the solubility of Pb, Zn, Cu, and Ni increases. Under experimental conditions, a reduction of 300 mV in Eh was enough to increase Cu, Ni, and Zn solubility fourfold (Green *et al.*, 2003).

Vanadium may occur in +2, +3, +4, and +5 oxidations states, from which $V_{(IV)}$ and $V_{(V)}$ are the dominant and more soluble species in moderately reducing and aerobic conditions. Reduction to $V_{(V)}$ decreases V mobility (Fox and Doner, 2002). Molybdenum may exist in nature in −4, −6 valence states, with $Mo_{(VI)}$ being the dominant species in oxic conditions.

In anoxic materials such as sediments, TEs are typically associated with OM, sulfides and, to a smaller extent, carbonates and other mineral fractions (Cantwell *et al.*, 2002). When reduced humic materials or sediments are exposed to oxidizing conditions for a long period, certain organic compounds and TEs such as Cd are released (Gambrell *et al.*, 1980; Motelica-Heino *et al.*, 2003). This happens because TE ions can form complexes with oxidized radicals, as documented for Cu^{2+}, Mn^{2+}, $Mo_{(V)}$, $Mo_{(III)}$, Cr^{3+}, $(VO)^{2+}$, and Fe^{3+} ions (Schnitzer, 2000). TEs are released also when sulfide precipitates (from slag tailing residues) are exposed to aerobic environment. Under anoxic conditions sulfides can effectively bind Zn and Cd (Lu and Chen, 1977). Oxidation of sulfide to sulfate in anaerobic dredged sediments results in the release of Cd, Ni, Pb, Zn, Fe, and Mn (Brooks *et al.*, 1968; Patrick *et al.*, 1977). When redox potential of polluted soils is changed to− 60 mV, dissolved concentrations of Cd and Pb decreased between pH 5 and 6 (Davranche and Bollinger, 2001).

F. Clay Content and Soil Structure

Clay-rich soils generally have higher retention capacity than soils with little or no clay (Murray *et al.*, 2004). Cation sorption on clay minerals varies depending on clay nature and cation properties. Vermiculites adsorbed twice as much Cs than illite and 20 times more than kaolinite in a single cation suspension (Tamura, 1972). The Pb and Cu adsorption was higher than Zn, Ni, and Cd adsorption on illite, beidellite, and montmorillonite. Desorption followed the trend Pb $>$ Cd $\gg$ Cu $>$ Ni $>$ Zn for beidellite and Pb $>$ Cd $=$ Cu $>$ Ni $>$ Zn for illite and montmorillonite (Rybicka *et al.*, 1995). Tiller *et al.* (1984) found a Pellustert (containing montmorillonite and kaolinite) adsorbed more Cd, Zn, and Ni than a Haplohumox or an Udalf (containing illite, kaolinite, chlorite, and quartz) at low pH value (4.5), while at high-pH values (>6.5) Cd and Ni adsorption capacity of Udalf was higher.

Selectivity of TE cation adsorption varies with clay minerals. Vermiculite is very effective for adsorbing Cu^{2+}, Pb^{2+}, Cd^{2+}, Zn^{2+}, and Ni, and the selectivity is greater than in montmorillonite, apparently due to more specific adsorption sites (Malla, 2002). But selectivity changes with cations, as Brigatti *et al.* (2004) found that montmorillonite adsorbed greater amount of Hg than vermiculite. Tiller *et al.* (1984) identified three reaction types, each having different affinities for cations: (1) those associated with iron oxides, which appeared to be controlled by metal ion hydrolysis; (2) those associated with organic colloids; and (3) those associated with 2:1 clay minerals with lower sensitivity to pH.

Proportion of nonspecifically sorbed elements is low in soils containing iron oxides. The sequence of metal cation selectivity is affected by the aging (weathering) of the soil, with younger soils, such as alfisol and ultisol, adsorbing more cations than older soils, such as Oxisol (Gomes *et al.*, 2001). Such affinity could be linked to the mineral composition. Abd-Elfattah and Wada (1981) observed the following selective adsorption:

$$\text{Pb} : \text{Fe-oxides}, \text{Ht}_{(\text{halloysite})}\text{A-Im}_{(\text{imogolite})},\text{A}_{(\text{allophane})} > \text{Humus}, \text{Kt}_{(\text{kaolinite})} > \text{Mt}_{(\text{montmorillonite})}$$

$$\text{Cu} : \text{Fe-oxides}, \text{Ht A-Im} > \text{Humus}, \text{Kt}, \text{A} > \text{Mt}$$

$$\text{Zn} : \text{Fe-oxides}, \text{Ht}, \text{A-Im} > \text{Kt} > \text{A}, \text{Humus} > \text{Mt}$$

$$\text{Cd} : \text{Fe-oxides} > \text{A-Im} > \text{A}, \text{Kt} > \text{Ht}, \text{Mt}$$

Surface complexation of metal cations at aluminol or silanol sites of allophane and imogolite depends on pH. The affinity sequence for cation adsorption on aluminol and silanol groups is still incomplete, but from the

order of decreasing affinity it can be viewed that the selectivity sequence depends on the molar Si/Al ratio (Harsh *et al.*, 2002).

Formation of clay–hydroxide complexes affects metal clay retention. Even at low pH, clay–Al hydroxide polymer complexes play an important role in metal binding, because the metal binding affinity for these complexes is greater than for pure Al hydroxides (Barnhisel and Bertsch, 1989; Janssen *et al.*, 2003; Keizer and Bruggenwert, 1991). Hydroxyaluminum and hydroxylaluminosilicate montmorillonite complexes are common in acid to slightly acid soils. These complexes adsorb much more Cd, Zn, and Pb than the single montmorillonite (Saha *et al.*, 2002). Elements such as $Cr_{(VI)}$ are adsorbed on Fe, Mn, and Al oxides, kaolinite and montmorillonite with hydroxyl groups on their surface (Davis and Lackie, 1980). However, small minerals such as lepidocrocite (γ-FeOOH) particles with adsorbed TEs can be mobilized with the drainage water (Roussel *et al.*, 2000).

Leaching experiments in lysimeters with repacked soils may underestimate metals transport, because they do not replicate well the natural pore structure and do not involve preferential flow through macropores, root channels, and cracks (Carey *et al.*, 1996). Any alteration of the soil structure may affect the hydraulic conductivity and the contact time between the soil and solute, before it is leached out of the soil profile. In structured soils the interaction between solid and solute is reduced, and the probability of TEs bypassing the soil matrix increases. Since the disturbance of the soil structure changes the connectivity of pores and the apparent water dispersion, the mobile water content in homogenized soils, as well as the water volume to displace the solute, increases (Cassel *et al.*, 1974).

Main factors affecting mobility or bioavailability of TEs in soils are summarized in Table II. The most important factors affecting TEs release from soil are pH, OM including DOM, and chemical speciation, while clay content and redox potential are less important.

V. TRANSPORT MODELING

Model development, its parameterization and validation for simulating transport of TEs is important for environmental impact assessment studies, as well as for research and teaching purposes. A large number of models of varying degree of complexity and dimensionality have been developed during the past several decades to quantify the basic physical and chemical processes affecting water flow and transport of TEs in the unsaturated zone (Šimůnek, 2005). Modeling approaches range from relatively simple analytical (Šimůnek *et al.*, 1999b; Toride *et al.*, 1995) and semianalytical solutions, to more complex numerical codes that permit consideration of a

Table II
Effects of Soil Factors on Trace Metal Mobility and/or Bioavailability[a]

Soil factor	Affected process	Effect on process
Low pH	Decreasing sorption of cations onto oxides of Fe and Mn	Increase
	Increasing sorption of anions onto oxides of Fe and Mn	Decrease
High pH	Increasing precipitation of cations as carbonates and hydroxides	Decrease
	Increasing sorption of cations onto oxides of Fe and Mn	Decrease
	Increasing complexation of certain cations by dissolved ligands	Increase
	Increasing sorption of cations onto (solid) humus material	Decrease
	Decreasing sorption of anions	Increase
High-clay content	Increasing ion exchange for trace cations (at all pH)	Decrease
High-swelling clays	Forming structured soils, which allow bypass flow	Increase
High OM (solid)	Increasing sorption of cations onto humus material	Increase
High-(soluble) humus content	Increasing complexation for most trace cations	Decrease/ increase
Competing ions	Increasing competition for sorption sites	Increase
Dissolved inorganic ligands	Increasing trace metal solubility	Increase
Fe and Mn oxides	Increasing sorption of trace cations with increasing pH	Decrease
	Increasing sorption of trace anions with decreasing pH	Decrease
Low redox	Decreasing solubility at low Eh as metal sulfides	Decrease
	Decreasing solution complexation with lower Eh	Increase/ decrease

[a]Adapted from Adriano (2001).

large number of simultaneous nonlinear processes for one (Šimůnek *et al.*, 1999a, 2005; Yeh *et al.*, 1992) or multiple (Jacques and Šimůnek, 2005; Steefel, 2000; Yeh and Cheng, 1999) solutes. While analytical and semianalytical solutions are still popular for some applications, the ever-increasing power of personal computers, and the development of more accurate and numerically stable solution techniques have motivated the much wider use of numerical codes in recent decades. The wide use of numerical models is also significantly enhanced by their availability in both the public and commercial domains, and by the development of sophisticated graphic-based interfaces that can substantially simplify their use (Šimůnek *et al.*, 1999a).

Although a large number of models exists, there are no models that consider all complex processes affecting transport of TEs. Soils often contain micro- and macropores, in which water moves preferentially in macropores and is stagnant in micropores, and in which there is no significant interaction

between the soil solution and the immobile phase. Structured soils may develop compacted peds and/or temporal cracks depending on the moisture conditions. Trace elements are affected by a multitude of complex, interactive physical, chemical and biological processes (Sections II.A and B). The transport and transformation of many TEs is further mediated by subsurface aerobic or anaerobic bacteria. Simulating these and related processes requires coupled reactive transport codes that integrate the physical processes of nonequilibrium/preferential variably saturated water flow and advective–dispersive solute transport with a range of biogeochemical processes. Models still need to be developed that would describe all these complex interactions.

A. Variably Saturated Water Flow

1. Uniform Flow

Predictions of water movement in the vadose zone are traditionally made using the Richards equation for variably saturated water flow. For a one-dimensional soil profile this equation is given by

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} - K(h)\right] - S \tag{10}$$

where θ is the volumetric water content (L^3L^{-3}), h is the soil water pressure head (L), t is time (T), z is distance from the soil surface downward (L), K is the hydraulic conductivity (LT^{-1}) as a function of h or θ, and S (T^{-1}) is the sink term accounting for root water uptake. Since Eq. (10) is a highly nonlinear partial differential equation, it is typically solved for specified initial and boundary conditions numerically, using finite differences or finite elements methods. Nonlinearity of the Richards equation is due to the nonlinearity in the soil hydraulic properties, which are characterized by the retention curve, $\theta(h)$, and the hydraulic conductivity function, $K(h)$. The soil hydraulic properties in numerical models are usually represented by two analytical functions, such as those developed by Brooks and Corey (1964), van Genuchten (1980), or Durner (1994).

2. Preferential Flow

Preferential flow in structured media (macroporous soils) can be described using a variety of dual-porosity, dual-permeability, multiporosity, and/or multipermeability models (Bodvarsson *et al.*, 2003; Gerke and

van Genuchten, 1993; Jarvis, 1994; Šimůnek *et al.*, 2003). Dual-porosity and dual-permeability models both assume that the porous medium consists of two interacting regions, one associated with the inter-aggregate, macropore, or fracture system, and the other one comprising micropores (or intra-aggregate pores) inside soil aggregates or the rock matrix. While dual-porosity models assume that water in the matrix is stagnant, dual-permeability models allow for water flow in the matrix as well.

Equation (10) can be extended for dual-porosity system as follows (Šimůnek *et al.*, 2003):

$$\begin{aligned} \theta &= \theta_m + \theta_{im} \\ \frac{\partial \theta_m}{\partial t} &= \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S_m - \Gamma_w \\ \frac{\partial \theta_{im}}{\partial t} &= -S_{im} + \Gamma_w \end{aligned} \tag{11}$$

where θ_m is the mobile (flowing) water content representing macropores or inter-aggregate pores (L^3L^{-3}), θ_{im} is the immobile (stagnant) water content representing micropores (matrix) or intra-aggregate regions (L^3L^{-3}), S_m and S_{im} are sink terms for both regions (T^{-1}), and Γ_w is the transfer rate for water from the inter- to the intra-aggregate pores (T^{-1}).

Available dual-permeability models differ mainly in how they implement water flow in and between the two pore regions. Approaches to calculating water flow in macropores or inter-aggregate pores range from those invoking Poiseuille's equation (Ahuja and Hebson, 1992), the Green and Ampt or Philip infiltration models (Ahuja and Hebson, 1992; Chen and Wagenet, 1992), the kinematic wave equation (Germann and Beven, 1985; Jarvis, 1994), and the Richards equation (Gerke and van Genuchten, 1993). Gerke and van Genuchten (1993) applied Richards equations to each of two pore regions. The flow equations for the macropore (fracture) (subscript f) and matrix (subscript m) pore systems in their approach are given by

$$\begin{aligned} \theta &= w\theta_f + (1 - w)\theta_m \\ \frac{\partial \theta_f(h_f)}{\partial t} &= \frac{\partial}{\partial z}\left[K_f(h_f)\left(\frac{\partial h_f}{\partial z} - 1\right)\right] - S_f\,(h_f) - \frac{\Gamma_w}{w} \\ \frac{\partial \theta_m(h_m)}{\partial t} &= \frac{\partial}{\partial z}\left[K_m(h_m)\left(\frac{\partial h_m}{\partial z} - 1\right)\right] - S_m\,(h_m) + \frac{\Gamma_w}{1 - w} \end{aligned} \tag{12}$$

respectively, where w is the ratio of the volumes of the macropore (or fracture or inter-aggregrate) domain and the total soil system (–). This approach

is relatively complicated in that the model requires characterization of water retention and hydraulic conductivity functions (potentially of different form) for both pore regions, as well as the hydraulic conductivity function of the fracture–matrix interface. Note that the water contents θ_f and θ_m in (12) have different meanings than in (11) where they represented water contents of the total pore space (i.e., $\theta = \theta_m + \theta_{im}$), while here they refer to water contents of the two separate (fracture or matrix) pore domains [i.e., $\theta = w\theta_f + (1-w)\theta_m$].

Multiporosity and/or multipermeability models are based on the same concept as dual-porosity and dual-permeability models, but include additional interacting pore regions (Gwo *et al.*, 1995; Hutson and Wagenet, 1995). For a recent comprehensive review of various modeling approaches used to simulate preferential flow see Šimůnek *et al.* (2003).

B. Solute Transport

1. Convection–Dispersion Equation

Under ideal soil conditions the convection–dispersion equation for reactive solutes can be used for modeling solute transport under unsaturated conditions:

$$\frac{\partial \rho s}{\partial t} + \frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z} - qc\right) - \phi \tag{13}$$

where s is the solute concentration associated with the solid phase of the soil (MM^{-1}, e.g., mol kg^{-1}), c is the solute concentration in the liquid phase (ML^{-3}, e.g., mol m^{-3}), ρ is the soil bulk density (ML^{-3}), θ is the volumetric water content (L^3L^{-3}), D is the solute dispersion coefficient (L^2T^{-1}) accounting for molecular diffusion and hydrodynamic dispersion, q is the volumetric fluid flux density (LT^{-1}) given by Darcy's law, and ϕ ($ML^{-3}T^{-1}$) is the reaction term representing sinks or sources for solutes. The element reactivity processes, such as ion exchange, precipitation–dissolution, and root solute uptake can be coupled to this equation through a reaction term ϕ (Hinz and Selim, 1994; Vogeler, 2001).

The governing transport Eq. (13) can be reformulated for volatile solutes residing and being transported also in the gaseous phase as follows:

$$\frac{\partial \rho s}{\partial t} + \frac{\partial \theta c}{\partial t} + \frac{\partial a c_g}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z} - qc\right) + \frac{\partial}{\partial z}\left(a D_g \frac{\partial c_g}{\partial z}\right) - \phi \tag{14}$$

where a is the air content (–), c_g is the concentration in the gaseous phase (ML^{-3}), and D_g is the diffusion coefficient (L^2T^{-1}) accounting for molecular diffusion in the gaseous phase. The liquid and gaseous concentrations are usually related using Henry's law.

2. Sorption

Soil can be viewed as a mixture of pure mineral substances, which together form a heterogeneous soil system. Adsorption of chemicals on these mixtures is commonly described with empirical models, since chemically meaningful models are difficult to apply (see Section II.A.2). The adsorption isotherm for TEs usually has a nonlinear shape. Linear adsorption isotherms could be expected for acid soil conditions and low concentrations. However, as the metal concentration increases the slope of the adsorption curve changes and thus the distribution K_d coefficient changes as well. Adsorption is usually very high in soils with pH higher than 6.5 and only traces of the element could remain in the solution (Section IV.A). In addition, desorption process can be very slow and therefore only negligible release of the TE to the soil solution is often observed. Adsorption–desorption process is often hysteretic, and thus a set of desorption isotherms can be obtained depending on the initial element concentration (Fig. 6) (Carrillo-Gonzalez, 2000). Desorption is often not completely reversible as a result of specific adsorption, precipitation, and/or occlusion reactions in the solid phase, and thus the activity of the TE in the soil solution can be easily overestimated. Since simpler models assume that solute adsorption is reversible, the amount of mobile TE can be overestimated and predicted concentrations can be higher than those observed.

Providing that the sorption of solute onto the solid phase is an instantaneous process, it can be described using empirical adsorption isotherms. Many numerical models use either the Freundlich [see also (2)]

$$s = K_d c^n \tag{15}$$

or Langmuir isotherms

$$s = \frac{s_{\max}\omega c}{1 + \omega c} \tag{16}$$

where K_d (L^3M^{-1}), n (–), and ω (L^3M^{-1}) are the empirical coefficients, and $s_{\max}$ is the adsorption maximum (MM^{-1}). General formulation that encompasses both Freundlich and Langmuir isotherms can also be used (Šimůnek *et al.*, 1999a):

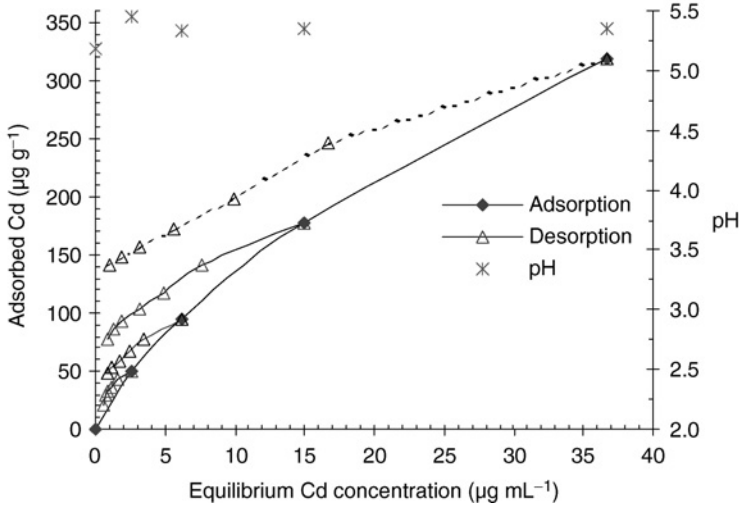


Figure 6 Adsorption–desorption isotherms of Cd in an agricultural sandy soil with 10 mM $CaCl_2$ as an electrolyte background (Carrillo-González, 2000).

$$s = \frac{K_d c^n}{1 + \omega c^n} \tag{17}$$

When $n = 1$, Eq. (17) becomes the Langmuir equation, when $\omega = 0$, Eq. (17) becomes the Freundlich equation, and when both $n = 1$ and $\omega = 0$, Eq. (17) leads to a linear adsorption isotherm (Šimůnek *et al.*, 1999a). Solute transport without adsorption is described with $K_d = 0$. Instantaneous sorption leads to the retardation of the solute transport that is characterized by the retardation factor R defined as:

$$R = 1 + \frac{\rho}{\theta}\frac{ds}{dc}\left(= 1 + \frac{\rho K_d}{\theta} \text{ for linear sorption}\right) \tag{18}$$

Kinetic nonequilibrium adsorption–desorption reactions are usually implemented using the concept of two-site sorption (Selim *et al.*, 1987; van Genuchten and Wagenet, 1989) that assumes that the sorption sites can be divided into two fractions. Sorption on one fraction of the sites (f, the type-1 sites) is assumed to be instantaneous, while sorption on the remaining (type-2) sites is considered to be time dependent. Sorption on the type-2 nonequilibrium sites is often assumed to be a first-order kinetic rate process.

$$\frac{\partial s_k}{\partial t} = \omega_k[(1 - f)s_e - s_k] - \phi_k \tag{19}$$

where f is the fraction of exchange sites assumed to be in equilibrium with the solution phase (–), ω_k is the first-order rate constant (T^{-1}), s_k is the sorption concentration on type-2 sites (MM^{-1}), s_e is the sorption concentration on type-2 sites at equilibrium (MM^{-1}), and ϕ_k is the reaction term for kinetic sorption sites ($MM^{-1}T^{-1}$). Depending on the value of the f parameter the two-site sorption model simplifies to either a fully kinetic ($f = 0$), or fully instantaneous ($f = 1$) sorption model.

Models based on the sorption isotherms are not sufficiently general to account for variations in sorption with pH, multiple oxidation states, electrostatic forces, and other factors. For these more complex conditions, surface complexation models, such as the constant capacitance, diffuse double layer, and triple layer models (Mattigod and Zachara, 1996), must be used. The various surface complexation models differ in their depiction of the interfacial region surrounding an adsorbent, that is, the number of considered planes and the charge-potential relationships.

Although many adsorption processes are more accurately described by more sophisticated surface complexation models, isotherm models have been successfully applied to the environmentally significant classes of neutral, relatively nonpolar organic compounds, such as chlorinated hydrocarbons and pesticides (Šimůnek and Valocchi, 2002), or As (Decker *et al.*, 2006a,b). In soils with significant fractions of organic carbon, these compounds adsorb primarily to solid-phase organic matter as a result of hydrophobic interactions, and the K_d of these compounds is often found to correlate directly with the organic carbon content of the soil.

3. Cation Exchange

In addition to sorption, TEs can be retarded due to additional chemical reactions, such as precipitation–dissolution, exchange of cations between those adsorbed on the soil surfaces and colloids, and those in the soil solution. Retention of TE (Me^{2+}) in soil (S) and under acid conditions can be described as a cation-exchange process. The exchange of any cation (Ca^{2+}) by a TE cation can be written as:



$$CaS_x + Me^{2+} \Leftrightarrow MeS_x + Ca^{2+} \tag{20}$$

with the corresponding exchange coefficient K_{MeCa}:

$$K_{MeCa} = \frac{q_{Me}\alpha_{Ca}}{q_{Ca}\alpha_{Me}} \tag{21}$$

where q is the adsorbed element and α is the activity of the free element in the solution. This exchange coefficient is derived for a binary system. It can be scaled to account for effects of various soil factors such as pH, background cation concentration, and the nature of the soil material. White and Zelazny (1986) provide a review of other general forms for cation selectivity coefficients, such as Gapon and Vanselow equations, that are commonly used to describe cation exchange.

4. Precipitation–Dissolution

Precipitation–dissolution process can be similarly considered as either instantaneous or kinetic (see also Section II.A). Equations describing precipitation–dissolution reactions are also obtained using the law of mass action, but contrary to the other processes, they are represented by inequalities rather than equalities, as follows (Šimůnek and Valocchi, 2002):

$$K_{\mathrm{p}} \geq Q_{\mathrm{p}} = \prod_{k=1}^{N_{\mathrm{a}}} (\alpha_k)^{a_k^{\mathrm{p}}} \tag{22}$$

where K_{p} is the thermodynamic equilibrium constant of the precipitated species, that is, the solubility product equilibrium constant, Q_{p} is the ion activity product of the precipitated species, a_k^{p} is the stoichiometric coefficient of the kth aqueous component in the precipitated species, α_k is the activity of the kth aqueous component, and N_{a} is the number of aqueous components. The inequality in (22) means that a particular precipitate is formed only when the solution is supersaturated with respect to its aqueous components; if the solution is undersaturated then the precipitated species (if it exists) will dissolve in order to reach equilibrium conditions. Equation (22) assumes that the activity of the precipitated species is equal to unity.

Precipitation–dissolution reactions are often orders of magnitude slower than other chemical reactions, while rates of dissolution of different minerals can also differ by orders of magnitude. Therefore, precipitation–dissolution reactions usually have to be considered as kinetic, rather than equilibrium reactions (e.g., Šimůnek and Valocchi, 2002). It is commonly assumed that the rate of precipitation–dissolution process is proportional to the disequilibrium of the system. Lichtner (1996) provided an excellent discussion of kinetics and related issues (the surface area, a moving boundary problem, a boundary layer, quasi-stationary states, and so on). Numerical models that account for cation exchange or precipitation–dissolution can not consider single solutes, but need to simulate simultaneous transport of multiple species that affect these processes.

5. Preferential Transport

Similarly as for water flow, preferential solute transport is usually described using dual-porosity (van Genuchten and Wagenet, 1989) and dual-permeability (Gerke and van Genuchten, 1993) models. The dual-porosity formulation is based on the convection–dispersion and mass balance equations as follows (van Genuchten and Wagenet, 1989):

$$\begin{aligned} \frac{\partial \theta_{\mathrm{m}} c_{\mathrm{m}}}{\partial t} + \frac{\partial f \rho s_{\mathrm{m}}}{\partial t} &= \frac{\partial}{\partial z}\left(\theta_{\mathrm{m}} D_{\mathrm{m}} \frac{\partial c_{\mathrm{m}}}{\partial z}\right) - \frac{\partial q c_{\mathrm{m}}}{\partial z} - \phi_{\mathrm{m}} - \Gamma_{\mathrm{s}} \\ \frac{\partial \theta_{\mathrm{im}} c_{\mathrm{im}}}{\partial t} + \frac{\partial (1-f) \rho s_{\mathrm{im}}}{\partial t} &= -\phi_{\mathrm{im}} + \Gamma_{\mathrm{s}} \end{aligned} \tag{23}$$

for the macropores (subscript m) and matrix (subscript im), respectively, where f is the dimensionless fraction of sorption sites in contact with the macropores (mobile water), and Γ_s is the solute transfer rate between the two regions ($ML^{-3}T^{-1}$).

Analogous to equations (12) for water flow, the dual-permeability formulation for solute transport can be based on advection–dispersion type equations for transport in both the fracture and matrix regions as follows (Gerke and van Genuchten, 1993):

$$\begin{aligned} \frac{\partial \theta_{\mathrm{f}} c_{\mathrm{f}}}{\partial t} + \frac{\partial \rho s_{\mathrm{f}}}{\partial t} &= \frac{\partial}{\partial z}\left(\theta_{\mathrm{f}} D_{\mathrm{f}} \frac{\partial c_{\mathrm{f}}}{\partial z}\right) - \frac{\partial q_{\mathrm{f}} c_{\mathrm{f}}}{\partial z} - \phi_{\mathrm{f}} - \frac{\Gamma_{\mathrm{s}}}{w} \\ \frac{\partial \theta_{\mathrm{m}} c_{\mathrm{m}}}{\partial t} + \frac{\partial \rho s_{\mathrm{m}}}{\partial t} &= \frac{\partial}{\partial z}\left(\theta_{\mathrm{m}} D_{\mathrm{m}} \frac{\partial c_{\mathrm{m}}}{\partial z}\right) - \frac{\partial q_{\mathrm{m}} c_{\mathrm{m}}}{\partial z} - \phi_{\mathrm{m}} + \frac{\Gamma_{\mathrm{s}}}{1-w} \end{aligned} \tag{24}$$

where the subscript f and m refer to the macroporous (fracture) and matrix pore systems, respectively; ϕ_f and ϕ_m represent sources or sinks in the macroporous and matrix domains ($ML^{-3}T^{-1}$), respectively; and w is the ratio of the volumes of the macropore domain (inter-aggregate) and the total soil systems (–). Equation (24) assumes complete advective–dispersive type transport descriptions for both the fractures and the matrix. Several authors simplified transport in the macropore domain, for example by considering only piston displacement of solutes (Ahuja and Hebson, 1992; Jarvis, 1994).

C. Colloid Transport and Colloid-Facilitated Solute Transport

Colloid-facilitated transport is a complex process that requires knowledge of colloid transport, dissolved contaminant transport, and colloid-facilitated contaminant transport. Colloids are inorganic and/or organic constituents that are generally chemically reactive. Inorganic colloids are primarily fine-sized mineral soil constituents, while organic colloids are organic matter based (Adriano, 2001). Transport equations must be formulated for both colloids and contaminants, in all their forms. Equations must be therefore written for the total contaminants, for contaminants sorbed kinetically or instantaneously to the solid phase, and for contaminants sorbed to mobile colloids, to colloids attached to the soil solid phase, and to colloids accumulating at the air–water interface. Presentation of all these equations is beyond the scope of this manuscript. Below we will give only selected equations (for colloid attachment–detachment, and total contaminant) from the total set of equations for colloid-facilitated transport that were recently incorporated in the HYDRUS software packages (Šimůnek *et al.*, 2006b; van Genuchten and Šimůnek, 2004). We refer readers to other literature for a complete description of the colloid-facilitated transport (Corapcioglu and Choi, 1996; Hornberger *et al.*, 1992; van Genuchten and Šimůnek, 2004).

Colloids are subject to the same subsurface fate and transport processes as chemical compounds, while additionally being subject to their own unique complexities (van Genuchten and Šimůnek, 2004). For example, many colloids are negatively charged so that they are electrostatically repelled by negatively charged solid surfaces. This phenomenon may lead to an anion exclusion process causing slightly enhanced transport relative to fluid flow. Size exclusion may similarly enhance the advective transport of colloids by limiting their presence and mobility to the larger pores (Bradford *et al.*, 2003). In addition, the transport of colloids is affected by filtration and straining in the porous matrix, which is a function of the size of the colloid, the water-filled pore size distribution, and the pore water velocity (Bradford *et al.*, 2003).

Colloid fate and transport models are commonly based on some form of the advection–dispersion equation [e.g., Eq. (13)], but modified to account for colloid filtration (Harvey and Garabedian, 1991) and the colloid accessibility of the pore space. The colloid mass transfer term between the aqueous and solid phases is traditionally given as:

$$\rho\frac{\partial s_{\mathrm{c}}}{\partial t} = \rho\frac{\partial\left(s_{\mathrm{c}}^{\mathrm{att}} + s_{\mathrm{c}}^{\mathrm{str}}\right)}{\partial t} = \theta_{\mathrm{w}} k_{\mathrm{ac}} \psi_{\mathrm{s}} c_{\mathrm{c}} - \rho k_{\mathrm{dc}} s_{\mathrm{c}}^{\mathrm{att}} + \theta_{\mathrm{w}} k_{\mathrm{str}} \psi_{\mathrm{str}} c_{\mathrm{c}} \tag{25}$$

in which c_{c} is the colloid concentration in the aqueous phase (nL^{-3}), s_{c} is the solid phase colloid concentration (nM^{-1}), ${s_{\mathrm{c}}}^{\mathrm{att}}$ and ${s_{\mathrm{c}}}^{\mathrm{str}}$ are the solid phase

colloid concentrations (nM^{-1}) due to colloid filtration and straining, respectively; θ_w is the volumetric water content accessible to colloids (L^3L^{-3}) (due to ion or size exclusion, θ_w may be smaller than the total volumetric water content θ, k_{ac}, k_{dc}, and k_{str} are first-order colloid attachment, detachment, and straining coefficients (T^{-1}), respectively, and ψ_s and ψ_{str} are a dimensionless colloid retention functions (–). The attachment coefficient is generally calculated using filtration theory (Logan *et al.*, 1995). To simulate reductions in the attachment coefficient due to filling of favorable sorption sites, ψ_s is sometimes assumed to decrease with increasing colloid mass retention.

At the same time, in addition to being subject to adsorption–desorption process at solid surfaces and straining in the porous matrix (Bradford *et al.*, 2003), colloids may accumulate at air–water interfaces (Thompson and Yates, 1999; Wan and Tokunaga, 2002; Wan and Wilson, 1994). A model similar to Eq. (25) may be used to describe the partitioning of colloids to the air–water interface

$$\frac{\partial A_{aw}\Gamma_c}{\partial t} = \theta_w \psi_{aca} k_{aca} c_c - A_{aw} k_{dca} \Gamma_c \tag{26}$$

where Γ_c is the colloid concentration adsorbed to the air–water interface (nL^{-2}), A_{aw} is the air–water interfacial area per unit volume (L^2L^{-3}), ψ_{aca} is a dimensionless colloid retention function for the air–water interface (–) similarly as used in Eq. (25), and k_{aca} and k_{dca} are the first-order colloid attachment and detachment coefficients to/from the air–water interface (T^{-1}), respectively.

The mass balance equation for the total contaminant, that is, the combined dissolved and colloid-facilitated contaminant transport equation (in one dimension) is given by (Šimůnek *et al.*, 2006b; van Genuchten and Šimůnek, 2004):

$$\frac{\partial \theta c}{\partial t} + \rho \frac{\partial s_e}{\partial t} + \rho \frac{\partial s_k}{\partial t} + \frac{\partial \theta_w s_c s_{mc}}{\partial t} + \rho \frac{\partial s_c s_{ic}}{\partial t} + \frac{\partial A_{aw} \Gamma_c s_{ac}}{\partial t} =$$
$$\frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z}\right) - \frac{\partial qc}{\partial z} + \frac{\partial}{\partial z}\left(\theta_w s_{mc} D_c \frac{\partial c_c}{\partial z}\right) - \frac{\partial q_c c_c S_{mc}}{\partial z} - \phi \tag{27}$$

where θ is the volumetric water content (L^3L^{-3}) (note that we use the entire water content for the contaminant), c is the dissolved contaminant concentration in the aqueous phase (ML^{-3}), s_e and s_k are contaminant concentrations sorbed instantaneously and kinetically, respectively, to the solid phase (MM^{-1}); s_{mc}, s_{ic}, and s_{ac} are contaminant concentrations sorbed to mobile and immobile (attached to solid and air–water interface) colloids (Mn^{-1}),

respectively; D is the dispersion coefficient for contaminants in solution (L^2T^{-1}), q is the volumetric water flux density for the contaminant (LT^{-1}), D_c is the dispersion coefficient for colloids (L^2T^{-1}), and q_c is the volumetric water flux density for colloids (LT^{-1}), and ϕ represents various chemical and biological reactions, such as degradation and production ($ML^{-3}T^{-1}$). Note that the left side sums up the mass of contaminant associated with the different phases (contaminant in the liquid phase, contaminant sorbed instantaneously and kinetically to the solid phase, and contaminant sorbed to mobile and immobile (attached to solid phase or air–water interface) colloids), while the right side considers various spatial mass fluxes (dispersion and advective transport of the dissolved contaminant, and dispersion and advective transport of contaminant sorbed to mobile colloids) and reactions. Additional partial differential equations need to be formulated to describe: (1) kinetic sorption of contaminant to the solid phase, (2) contaminant sorbed to mobile colloids, and (3) contaminant sorbed to immobile (attached to solid and air–water interface) colloids (Šimůnek *et al.*, 2006b; van Genuchten and Šimůnek, 2004).

VI. MODEL APPLICATIONS AND CASE STUDIES

Since there has already been a very large number of applications of model of varying degree of complexity reported in the literature, we give below only selected examples of these applications. We divided them into two main groups. Single-component models, that is, models that consider transport of single solutes without considering implicitly simultaneous transport of other solutes and their mutual interactions, represent the first group of applications. Multicomponent models, that is, models that simulate simultaneous transport and interactions of multiple solutes, represent the second group.

A. Single-Component Models

Simons used successfully a simple model for describing salts movement in soils (Rowell, 1994). In this model the soil is divided into a number of layers, while each layer is assumed to be spatially homogeneous with the constant concentration. The simulations were carried out using a single distribution constant, but could be improved when the adsorption behavior was properly modeled. Černík *et al.* (1994) used convection–dispersion and stochastic convection models (both linear) to explain the Cu and Zn concentrations in the soil profile, deposited from metal smelter. Carey *et al.* (1996) proposed to describe a nonsymmetrical sigmoidal shape of the breakthrough curves

using the double exponential biomass growth model, known as the Gompertz equation. Petersen and Petrie (1999) developed a transport reaction model for heap leaching, in which kinetic and equilibrium reactions of the trace elements can be incorporated. In this model the soil column is divided into a number of layers, in which the bulk concentration is assumed spatially constant. They suggested that this is a good model for environmental risk assessment studies. Vogeler *et al.* (2001) used a model based on the numerical solution of the Richards and convection–dispersion equations (see Section V) to reliably predict movements of copper and bromide through the soil, into which a chelating agent (EDTA) had been added to increase the solubility of TEs for plant uptake during phytoremediation. Seuntjens *et al.* (2001) used water flow and solute transport numerical model HYDRUS-1D (Šimůnek *et al.*, 1998) to evaluate effects of aging on cadmium transport in undisturbed contaminated sandy soil columns. Similarly, Bahaminyakamwe *et al.* (2006) used HYDRUS-1D to simulate copper mobility in soils as affected by sewage sludge and low molecular weight organic acids.

Models simulating leaching of solutes through porous media are often based on the convection–dispersion equation and usually have significant limitations for application to natural soil conditions. Convection–dispersion-equation based models are well suited to homogeneous repacked soils, fully saturated, steady-state flow conditions, and a simple pulse injection of contaminants (Jarvis *et al.*, 1999). However, it is often reported that mass flow in the soil matrix provides only a minor contribution to element transport and that preferential transport through macropores and cracks dominates the trace element transport. Modeling of these phenomena still represents an important challenge.

Most computer programs modeling the transport of TEs have described adsorption using the distribution coefficient. But the sorption process is often different from the desorption process, and the concentration of the TE in the solution is also directly determined by the rate of desorption. Zachara *et al.* (1993) modeled the Cd leaching using the K_d value calculated from desorption isotherms. In steady-state flow experiments, Tran *et al.* (1998) observed an anomalous increase of the Cd concentration in the solution during interruption of the flow. This indicated that Cd was desorbed kinetically during the interruption period.

Considering the distribution coefficient to be constant for all soil layers may lead to an improper evaluation of the sorption phenomena and to serious errors in predicting contaminant transport through unsaturated soils (Elzahabi and Yong, 2001). In order to properly simulate movement of TEs in soils, it is necessary to consider different adsorption coefficients and rates for different soil layers. Competition between TEs for sorption sites may also affect the retardation of some elements. Since there is not enough information available about

this process, more research about the interaction and competition among TEs during transport is needed.

Models simulating solute movement in structured soils must provide at least two essential features. They must describe effects of naturally occurring particles on the TE transport and simulate water flow and particle transport in structural macropores (White, 1985). Models should also be able to describe transient water flow and solute transport in layered, subsurface drained, macroporous soil (Jarvis, 1994). MACRO is one of such models that provide majority of required features and that was applied successfully to describe pesticide transport at the field scale (Besien *et al.*, 1997). The latest version of HYDRUS-1D (Šimůnek *et al.*, 2005) also provides several different approaches to simulate preferential flow and transport using various dual-porosity and dual-permeability concepts (Pot *et al.*, 2005; Šimůnek *et al.*, 2003), as well as modules to simulate colloid transport and colloid facilitated solute transport (Šimůnek *et al.*, 2006b; van Genuchten and Šimůnek, 2004).

B. Multicomponent Models

Contrary to single-component models that consider transport of only one solute and thus can not dynamically adjust behavior of this solute in response to other solutes present, multicomponent models simultaneously simulate transport of multiple solutes, and thus behavior of one solute can react to the presence of other solutes. Multiple solutes can mutually compete for sorption sites, can create various aqueous complexes, and can precipitate or dissolve depending on actual conditions in the soil profile.

Many environmental applications of reactive multispecies solute transport models appeared in the literature during the last two decades. For example, water leaching from various tailing piles (such as from uranium mills) often contains many trace metals including molybdenum, selenium, arsenic, and chromium (Brookins, 1984). Using the HYDROGEOCHEM model, Yeh and Tripathi (1991) simulated the release of trace metals and acidity from an acidic uranium mill tailings pile. Narasimhan *et al.* (1986) used the DYNAMIX model to study groundwater contamination from an inactive uranium mill tailings pile. Walter *et al.* (1994), Lichtner (1996), and Gerke *et al.* (1998) carried out similar studies. Another significant challenge is to design and evaluate facilities for a safe disposal and long term isolation of radioactive waste, especially high-level nuclear waste. The migration of neptunium between the repository and the ground water table after a hypothetical repository breach at the potential high-level nuclear waste repository at Yucca Mountain, Nevada, was studied using a multicomponent solute transport model by Viswanathan *et al.* (1998). Fate of metal-organic mixed wastes was studied by Rittmann

and VanBriesen (1996) and VanBriesen (1998). An example of a biogeochemical multicomponent model is PHREEQC (Parkhurst and Appelo, 1999) that was, for example, used to simulate Cd and Zn transport by Voegelin and Kretzschmar (2003). Significant limitation of the PHREEQC and many other models, however, is that they can consider only one-dimensional or steady-state water flow conditions.

The more general geochemical transport modeling approach was used recently in several codes that coupled transient unsaturated flow to general biogeochemistry models. These include 3DHYDROGEOCHEM (Yeh and Cheng, 1999), CORE^{2D} (Samper *et al.*, 2000), MIN3P (Mayer *et al.*, 2002), RETRASO (Saaltink *et al.*, 2004) and HP1 (Jacques and Šimůnek, 2005). In the multicomponent transport model of Jacques and Šimůnek (2005) the HYDRUS-1D water flow and solute transport model (Šimůnek *et al.*, 1998) was coupled with the PHREEQC geochemical speciation model (Parkhurst and Appelo, 1999). PHREEQC considers a variety of chemical reactions, such as aqueous speciation; gas, aqueous, and mineral equilibrium; oxidation–reduction reactions; and solid-solution, surface-complexation, ion-exchange, and kinetic reactions, while HYDRUS-1D considers transient variably saturated water flow and heat and solute transport for both homogeneous and heterogeneous soil profiles. The combined HYDRUS1D-PHREEQC model, HP1 (Jacques and Šimunek, 2005) permits simultaneous simulations of variably saturated transient water flow, multicomponent solute transport, and speciation and other geochemical processes, including a broad range of mixed equilibrium and kinetic reactions.

Jacques *et al.* (2002, 2003) and Šimunek *et al.* (2006a) presented several examples that illustrate the potential power and versatility of the coupled multicomponent geochemical modeling approach used in HP1. The first example solved the hypothetical problem dealing with the multicomponent transport of major cations (Al, Ca, K, Na, and Mg), anions (Cl and Br), and three trace metals (Cd, Pb, and Zn) in a saturated short soil column. In this example, a fully saturated 8-cm long vertical soil column having an initial solution defined as "Initial" aqueous solution in Table III and its ion-exchange complex in equilibrium with this solution was considered. This problem simulates leaching of Cd, Pb, and Zn from an initially contaminated soil core using Ca-rich leaching water. Removal of trace metals from the solid phase was calculated by ion exchange with Ca, and to a lesser degree with Mg. Water was applied to the top of the column at a steady rate of 2 cm day^{-1} and having a chemical composition as given by "Boundary" aqueous solution in Table III. Dispersivity was considered to be 0.2 cm, and CEC equal to 11 mmol per cell. Resulting outflow concentrations at the outlet are shown in Fig. 7.

The second example simulated trace metal transport in a multilayered soil profile assuming steady-state water flow and pH-dependent cation-exchange

Table III
Main Components, Complex Species, and Exchange Species (X Refers to Ion Exchanger) Considered in the HP1 Simulation of the Leaching of Trace Metals from a Short Laboratory Column (Jacques *et al.*, 2002)

Components	Species	Aqueous solutions (mmol liter^{-1})	
		Boundary	Initial
Al	Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^+$, $Al(OH)_3$, $Al(OH)_4^-$	0.1	0.5
Br	Br^-	3.7	11.9
Cl	Cl^- (and Cd, Pb, and Zn-species)	10	0.0
Ca	Ca^{2+}, $Ca(OH)^+$	5	0.0
K	K^+, KOH	0	2
Na	Na^+, NaOH	0	6
Mg	Mg^{2+}, $Mg(OH)^+$	1	0.75
Cd	Cd^{2+}, $Cd(OH)^+$, $Cd(OH)_2$, $Cd(OH)_3^-$, $Cd(OH)_4^{2-}$, $CdCl^+$, $CdCl_2$, $CdCl_3^-$	0	0.09
Pb	Pb^{2+}, $Pb(OH)^+$, $Pb(OH)_2$, $Pb(OH)_3^-$, $Pb(OH)_4^{2-}$, $PbCl^+$, $PbCl_2$, $PbCl_3{}^-$, $PbCl_4^{2-}$	0	0.1
Zn	Zn^{2+}, $Zn(OH)^+$, $Zn(OH)_2$, $Zn(OH)_3{}^-$, $Zn(OH)_4^{2-}$, $ZnCl^+$, $ZnCl_2$, $ZnCl_3{}^-$, $ZnCl_4^{2-}$	0	0.25
X	AlX_3, $AlOHX_2$, CaX_2, CdX_2, KX, NaX, MgX_2, PbX_2, ZnX_2 (mmol)	0	11.0

Aqueous solutions initially in the soil profile (Initial) and applied as the boundary condition (Boundary).

capacities. The third example extended the analysis to variably saturated flow by simulating the long-term fate and transport of trace metals under transient field conditions. This example demonstrated that transient simulations resulted in dramatically different predictions than those based on steady-state water flow. Total concentrations were up to one order of magnitude higher than those obtained assuming steady-state flow. This was mainly caused by fluctuating pH in the transient case that caused significantly different mobility of trace metals throughout the year and resulted in significantly more leaching compared to the case of steady-state flow. All three examples were limited to aqueous speciation and equilibrium ion-exchange reactions. Yet another problem simulated based on a study of Adler (2001) the intrusion of a high-pH solution (pH 13) into a compacted clay core leading to kinetic dissolution of primary minerals (kaolinite, illite, quartz, calcite, dolomite, and gypsum) and precipitation of secondary minerals (sepiolite and hydrotalcite).

The effect of inorganic ligands (Cl) in the soil solution on the Cd transport has been demonstrated by Jacques *et al.* (2004), who investigated undisturbed 1-m long, 0.8-m wide lysimeter experiments under quasi steady-state flow conditions. During leaching with 0.005 M $CaCl_2$, a 1-day pulse

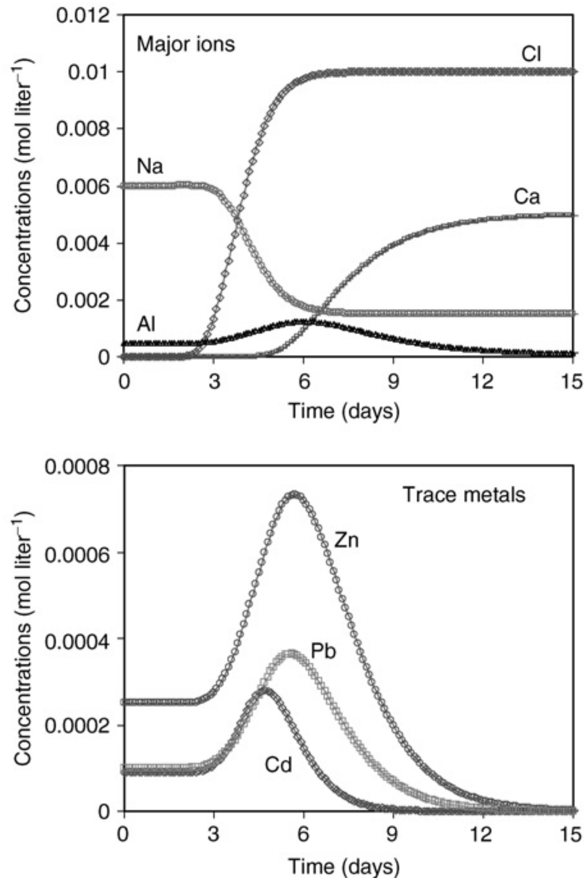


Figure 7 Outflow concentrations of selected major cations (top) and heavy metals (bottom) calculated using HP1 during steady-state saturated flow.

of 0.05 M $CaCl_2$ was given to mobilize Cd. The inflow of Cl-rich water clearly enhanced the leaching of Cd due to exchange with Ca and a mere mobile inorganic complex forming with chloride. A coupled reactive transport model for unsaturated transient flow conditions HP1 (Jacques and Šimůnek, 2005) was used to describe the experiments. Adsorption of Cd, some other trace metals (Cu, Pb, Zn) and major cations (Mg, Ca, Na, K) was described with a (multisite) cation-exchange complex model. Outflow concentrations of these components were modeled for a series of Cl-poor and Cl-rich water applications.

In yet another example, Jacques *et al.* (2005) evaluated the impact of long-term applications of mineral fertilizers ((super)phosphates) containing small

amounts of ^{238}U and ^{230}Th to agricultural soils. Field soils that receive P-fertilizers accumulate U and Th and their daughter nuclides, which may eventually leach to groundwater. They used the HP1 code that accounted for interactions between U and organic matter, phosphate, and carbonate, considered surface complexation as the major solid phase interaction, and coupled all geochemical processes with transient soil water flow. Jacques *et al.* (2005) carried out calculations using a semisynthetic 200-year long time series of climatological data for Belgium and evaluated U fluxes into the groundwater. These examples show that the coupling of HYDRUS-1D and PHREEQC leads to a potentially very powerful tool for simulating a broad range of interacting physical, chemical and biological processes affecting the transport of TEs in soils.

Although the HP1 model can consider a broad range of interactions, it can not simulate preferential flow and transport or colloid-facilitated transport. Although individual models do exist that can simulate either: (1) preferential flow and transport, (2) colloid-facilitated transport, or (3) a broad range of interacting physical, chemical and biological processes, there is, to the best of our knowledge, at present not a single model that could consider all these processes and interactions simultaneously.

VII. SUMMARY AND CONCLUSIONS

In this chapter, we portrayed soils as a heterogeneous mixture of biotic (i.e., organic matter, organic residues including biosolids, xenobiotics, and pesticides, plant roots and debris, soil animals including invertebrates, microbes and microbial metabolites, and so on.) and abiotic (i.e., clay minerals, other aluminosilicate minerals, salts, precipitates, miscellaneous inorganic materials such as metals, coal residues, and mining residues, and so on) materials. In turn, TE dynamics in soils is governed by biotic and abiotic processes, the latter including complexation, adsorption–desorption, precipitation–dissolution, redox reactions, and catalysis. In other words, soil is a dynamic system in which continuous interaction takes place between soil minerals, organic matter, and organisms. Each of these soil components influences the physicochemical and biological properties of the terrestrial systems.

We then viewed the soil as a physicobiogeochemical filter of contaminants either in a solute, particulate or colloidal form. Mechanisms moderating biogeochemical sequestration of TEs indicate that sorption–desorption reactions, especially in severely contaminated soils, largely regulate the extent of partitioning, typically measured as Kd, in the soil-solution matrix. Sorption in this case includes precipitation, occlusion, and adsorption while desorption includes dissolution. These mechanisms are, in turn, moderated by

certain factors, the most important of which include pH, OM, and chemical speciation of the element. Biological processes augment the processes above especially in typical surface soils and rhizosphere but may be limited in severely contaminated environments due to biotoxicity to organisms. The rhizosphere represents a microenvironment in soils where biological processes, by virtue of root activity, root exudates and prolific microbial consortia can assume an important role in TE dynamics. Microbes may bioaccumulate and promote biosorption of TEs, with certain microorganisms mediating redox transformation of multivalence elements such as Cr, As, Se, Fe, Mn, and so on. In general, TE partitioning in soils is dependent on the element type, chemical speciation of the element, and soil properties and conditions. Thus the extent of partitioning in soils is rather difficult to predict. However, limited success in predicting adsorption on soil for B, Mo, Mn, and As has been accomplished using surface complexation models.

When the capacity of the soil components to sequester TEs has become limited, substantial amounts of these TEs can be desorbed, mobilized and eventually transported through the soil profile, the vadose zone and ground waters. Both organic (e.g., low-molecular-weight organic acids, such as fulvic acids, and other organic acids from root exudates, decay of plant, animal, and microbial tissues, microbial metabolites, and high-molecular-weight organic acids such as humic acids) and inorganic (e.g., chlorides, sulfates, nitrates, phosphates, and so on) ligands could promote TE dissolution/desorption and serve as transport vectors thereby enhancing leaching through mass flow and diffusion. These ligands form soluble, stable TE–ligand complexes that render them more mobile and bioavailable. Although leaching plays only a minor role in the vertical transport of cationic elements, it represents an important transport vector for anionic elements such as Se, Cr, and As. Cationic elements move to significant vertical distances only under rare, specific soil conditions such as acidic sandy soils or in association with reactive, mobile colloids. Facilitated solute transport can occur in the presence of highly reactive colloids of either organic, that is, OM based, and inorganic (e.g., clay minerals, and so on) forms. In general, transport of solutes, colloids, and particulates is enhanced under field, structured soils with macropores or in cracked soils.

While there are models applicable to preferential and nonequilibrium water flow and solute transport in structured soils and fractured rocks, models dealing with the colloid transport and colloid-facilitated solute transport that consider complex reactions between colloids and the soil solid phase, and the air–water interface, as well as between contaminant and colloids in different states (mobile and/or immobile), are being actively developed. Also significant efforts to combine variably saturated flow and transport models with biogeochemical models (e.g., coupled HYDRUS-1D–PHREEQC) that can take into account various interacting geochemical and biological reactions under variable conditions are underway. To the best of

our knowledge, there are no models available at present that address all these interactive processes in their full complexity. Additionally, further integration of various types of models is necessary to address practical problems in the transport of TEs in the subsurface environment. However, advanced methodologies and techniques should precede such efforts in order to simplify and understand these complex processes and how they behave in inherently heterogeneous subsurface environment and the stochastic nature of boundary conditions in these systems.

In summary, understanding various physicobiogeochemical processes and how they are affected by certain factors such as pH, OM, and so on, is necessary to predict TE partitioning in soils. Such more accurate prediction of the TE behavior in the soil-solution phase is vital to more accurately predict the subsequent mobility and transport of these substances in the soil profile and the subsurface environment. Advances in this field have become imminent by virtue of the efforts to couple the conventional variably saturated flow and transport models with biogeochemical models with the desire to address interactive, complex processes in heterogeneous systems.

ACKNOWLEDGMENTS

The National Council of Science and Technology of Mexico has partially supported the work research of Dr. Carrillo under the projects research No. 135567-B and SEMARNAT-CONACyT CO-01-2002-739.

Dr. Šimůnek's work was supported in part by Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) under the STC Program of the National Science Foundation, Agreement No. EAR-9876800 and the Terrestrial Sciences Program of the Army Research Office (Terrestrial Processes and Landscape Dynamics and Terrestrial System Modeling and Model Integration).

Ongoing research in Dr. Sauvé's laboratory is supported in part by the Natural Sciences and Engineering Research Council of Canada.

A grant from the Biocomplexity in the environment and International Programs of the National Science Foundation (#0322042) enabled Professor Adriano to cooperate in this chapter.

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THE AGRONOMY AND ECONOMY OF CARDAMOM (*ELETTARIA CARDAMOMUM* M.): THE "QUEEN OF SPICES"

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Advances in Agronomy, Volume 91

0065-2113/06 $35.00
DOI: 10.1016/S0065-2113(06)91004-9

Cardamom, popularly known as the "Queen of Spices," has a checkered history, dating back to the *Vedic* period (ca. 3000 BC) and is among the ingredients poured into the sacrificial fire during the Hindu marriage. Today cardamom commands a leading position among the spices of immense commercial importance and is finding its way into the dietary habits of millions around the world, even among people on the European and North American continents, hitherto unaccustomed to its use. Cardamom use ranges from a simple dietary constituent to that of immense pharmacological benefits. Although beset with many problems, both agronomic and economic, it is a safe bet that next to black pepper, cardamom will emerge in the world market as a spice of immense commercial importance. Although India was the world leader in cardamom production, starting from the 1970s the country began to slide down both in production and productivity, while Guatemala, took the leading position, although the cardamom produced there is of inferior quality. Among the primary constraints of production, is the absence of an ideotype that combines many positive traits to boost production potential, while at the same time resisting the ravages of the devastating viral disease *Katte* of the Karnataka State in southern India. Fertility management of cardamom soils is still rooted in classic "textbook knowledge." This exhaustive chapter covering many aspects of the agronomy and economy of cardamom production, has also a separate chapter on the

relevance of "*The Nutrient Buffer Power Concept*," developed by the author, in enhancing cardamom productivity.

I. INTRODUCTION

Cardamom, popularly known as the "Queen of Spices" is the second most important spice crop in the world, next to black pepper (*Piper nigrum*), which is known as the "King of Spices." The description "Queen of Spices" is because cardamom has a very pleasant aroma and taste and is a highly valued spice since time immemorial. It belongs to the genus *Elettaria* and species *cardamomum* (Maton). The term *Elettaria*, which is the generic name, has its origin in the colloquial word Elettari (in Tamil, one of the popular South Indian languages) referring to the cardamom seeds. In the original description it means a "particle/seed of the leaf." It is a large-sized perennial, herbaceous rhizomatous monocot, which belongs to the Zingiberaceae family. The plant is extensively grown in the hilly tracts of southern India at elevation ranging from 800 to 1500 m. It grows as an under crop, beneath forest trees as it grows best in shade and cool climate at high elevations. It is grown in Sri Lanka, Papua New Guinea (PNG), and Tanzania on the African continent. Within Latin America, Guatemala is the biggest grower of cardamom. Guatemala is also the biggest competitor to Indian cardamom in the world market.

A. Historical Background of Cardamom

Cardamom has an interesting history dating back to Vedic times, about 3000 years BC. In the ancient Indian language Sanskrit, it is referred to as "Ela." In ancient times of the Hindu culture, sacrificial fire was a common ritual and mention of cardamom as an ingredient of the mixture of several materials into the sacrificial fire, solemnizing a Hindu marriage has been mentioned in ancient texts (Mahindru, 1982). *Charaka Samhita* and *Susrutha Samhita*, the ancient Indian Ayurvedic texts, written in the post-Vedic period (1400–1600 BC) make a mention of cardamom. However, it is not precisely known whether cardamom, referred to as Ela, in these texts, pertain to the Indian variety or the large Nepalese variety. Assyrians and Babylonians were familiar with medicinal plants, and among the 200 odd plants that the former dealt with, cardamom was one (Parry, 1969). It was mentioned that the ancient king of Babylon, Merodach-Baladan II (721–702 BC) grew cardamom among other herbs in his garden. Surprisingly, there was no mention of

cardamom in the ancient Egyptian texts, unlike that of pepper. Possibly, cardamom was just beginning to reach Assyria and Babylonia through the land routes. Interestingly reference to cardamom has been seen in the ancient Greek and Roman texts. Spices were the symbols of royalty and luxury and cardamom was used in the manufacture of perfumes during the Greek and Roman times. In addition, cardamom was also used as an aphrodisiac (Parry, 1969). Significantly, the Greek physician and author of the legendary *Materia Medica*, Dioscorides (40–90 AD) makes a mention of cardamom in his work. Cardamom was widely used to aid digestion and that was the most important reason both the Greeks and Romans imported the same in large quantities from India. Thus, it became one of the most popular oriental spices in Greek and Roman cuisine. This led to cardamom being listed as a dutiable item in Alexandria in 176 AD.

Linschoten in the *Journal of Indian Travels* (1596) describes two types of cardamom in use in southern India, the "greater" (large) and "lesser" (small) types. This would suggest that the large cardamom found extensively in Nepal must have been finding its way to southern India through land routes, brought by travelers dating back to nearly 4000 years. Dymock while referring to the introduction of cardamom to Europe writes, "When they were first introduced into Europe is doubtful, as their identity with the *Amomum* and *Cardamomum* of the Greeks and Romans cannot be proved." Linschoten writes about lesser cardamom as "it mostly is grown in Calicut and Cannanore, places on the coast of Malabar." Paludanus, a contemporary of Linschoten, wrote that according to Avicenna, there are two kinds of cardamoms, "greater" and the "lesser" and continues to add that cardamom was unknown to the Greeks such as Galen and Dioscorides. Galen in his Seventh Book of *Simples* wrote, "cardamom is not so hot as Nasturtium or water cresses," "but pleasanter of savor and smell with some small bitterness." The properties indicated were dissimilar to that of the Indian cardamom. Dioscorides in his First Book commented on the cardamom brought from Armenia and Bosphorus and added that "we must choose that which is full, and tough in breaking, sharp and bitter of taste, and smell there of, which cause heaviness in a man's head (Watt, 1872). Obviously, Dioscorides was writing not about Indian cardamom, but other distinctly different plant. Such references led Paludanus (Watt, 1872) to infer that the *Amomum* and *Cardamomum* of the ancient Greeks were not the spices of India. On the whole, references to cardamom in ancient and early centuries of the Christian era and even in the middle ages are but scanty compared to black pepper. Even Auboyar in his classic work on day-to-day living in ancient India (200 BC to 700 AD) makes only a fleeting mention of cardamom (Mahindru, 1982).

The Mediterranean merchants were clearly cheated by the Arabs on the sea route through which the latter brought home the spices from India. Like pepper, cardamom was no exception. Pliny thought that cardamom was grown in Arabia. This belief persisted until the discovery of the sea route to

India and the Portuguese landed on the west coast of India. This coincided with the ending of the Arab monopoly on spice trade, and the Portuguese started shipping out pepper, cardamom, and ginger to Europe. Since the European colonizers were more interested in procuring pepper and ginger both crops took hold in India, the former, in particular along the Malabar Coast. Cardamom was relegated to the back seat. This was the case in the period from sixteenth to eighteenth centuries. Cardamom was considered a minor forest produce. It is only in the beginning of the nineteenth century that cardamom plantations were established, but it was interplanted with coffee. But, its cultivation spread rapidly in the Western Ghats and the region south of Palakkad (the midsouthern district of Kerala) became to be known as Cardamom Hills.

The earliest written evidence of cardamom growing in India was that of the officers working for the British East India Company. The most important among these written pieces was that of Ludlow, an Assistant Conservator of Forests. Others were the *Pharmacographia, Madras Manual*, and *Rice Manual*. A brief description of cardamom cultivation in South India was also given by Watt (1872). The system of cardamom collection from naturally growing plants continued until 1803 but demand escalated in later years and this naturally led to establishment of large-scale plantations in India and Sri Lanka, what was then known as Ceylon (Ridley, 1912). In two erstwhile states of Travancore and Cochin, within the entire state of Kerala, which had their own Kings, cardamom was a monopoly of the respective governments. The Raja (King) of Travancore mandated that all the cardamom produced be sold to his official representative and sent to a central depot in the Alleppey town in central Kerala, which was then a state port. Here the produce was sold by auction. Principal buyers were Muslims and the best lot, known as "Alleppey Green," was reserved for export. In the forestland in the state of Kerala, owned by the then British government, cardamom was considered as a "miscellaneous produce," while in the neighboring Coorg district in the state of Karnataka, forestlands were leased out to private cultivators of cardamom. Leghorn, the Conservator of Forests in the Madras Presidency (earlier nomenclature that included four southern states, namely, Kerala, Karnataka, Madras, and Andhra, which have all become independent since then), the spread of coffee eclipsed that of cardamom in many areas of "Malabar Mountains"—a reference to Western Ghats (Watt, 1872). In the *Madras Manual* reference to cardamom cultivation was seen. It was mentioned "In the hills of Travancore cardamom grows spontaneously in the deep shades of the forests: it resembles somewhat turmeric and ginger plants but grows to a height of 6–10 ft, and throws out the long shoots which bear the cardamom pods." The following passage describes cardamom management. "The owners of the gardens, early in the season come up from the low country east of the Ghats, cut the brushwood and burn the creepers and otherwise clear the soil for the growth of the plants as soon as the rains fall. They come back to gather the cardamom when

they ripen, about October or November" (Watt, 1872). One can surmise from the writings of the British officials that a process of bleaching used to be carried out in Karnataka, and this was done by transporting cardamom to Havre, a place in Dharma district of Karnataka, and the bleaching process was done using the water from a specific well which resulted in enhancement of flavor in the dried product (Watt, 1872). A bleaching method is elaborately described by Mollison (1900) where soapnut water was used.

B. Cardamom Production, Productivity: A World View

Presently cardamom production is primarily concentrated in India and Guatemala. Cardamom was introduced to Guatemala in 1920, most likely either from India or Sri Lanka, by a New York broker and was planted in the vicinity of Coban in the department of Alta Verapaz (Lawrence, 1978). After the World War II, cardamom production in Guatemala increased substantially on account of shortage in production and high prices and Guatemala soon became the top cardamom producer in the world. The natives do not relish the taste of cardamom and the entire quantity produced is exported. Today Guatemala produces about 13,000–14,000 t of cardamom annually. Table I gives a world view of cardamom production and productivity.

Table I
Cardamom Production in the World

Time span	Percentage share of total			World production (mt)
	India	Guatemala	Others[a]	
1970/71–1974/1975	65.4	21.5	13.1	4678
1975/76–1979/1980	53.7	34.5	11.8	6628
1980–1981	42.9	48.8	8.3	10,250
1984–1985	31.9	60.3	7.8	12,220
1985/1986–1989/1990	26.5	67.5	6.0	14,392
1990/1991–1994/1995	28.4	65.6	6.0	19,470
1995/1996–1997/1998	29.8	64.2	6.0	24,953

[a]Estimates, actual figures unavailable.

Source: Cardamom Statistics, 1984–1985, Cardamom Board, Government of India, Cochin, Kerala State.

Spices Statistics, 1997 Spices Board, Government of India, Cochin, Kerala State.

All India Final Estimate of Cardamom, 1997/1998, Government of India, Ministry of Agriculture.

Important note: In three decades the percentage contribution of India to total production plummeted by 54%, while Guatemala increased it by 199%. Other countries in the same period had a similar decline of 54% like that of India, thus, Guatemala takes the leading position in cardamom production in the world.

In India the cardamom area has come down during the last two decades from 1,05,000 ha in 1987–1988 to 69,820 ha in 1997–1998—a decrease of 33.5%. Production increased from 3200 t during 1987–1988 to 9290 t in 1999–2000—an increase of 190%. During the same period, productivity has increased from 47 to 173 kg ha^{-1}—an increase of 268%. Cardamom cultivation is primarily confined to three South Indian states, namely, Kerala, Karnataka, and Tamil Nadu. Kerala has 59% of the total area cultivated and contributes 70% of the total production. Karnataka has 34% of total area cultivated and contributes 23% to total production, while Tamil Nadu has 7% area and contributes the same percentage to total production. Most of the cardamom-growing areas in Kerala are located in the districts of Idukki, Palakkad, and Waynad. In Karnataka, the crop is grown in the districts of Coorg, Chickmagalur, and Hassan and, to some extent, in North Kanara district. In Tamil Nadu, cardamom cultivation is located in certain places of Pulney and Kodai hills. On the whole, in India, cardamom is small land holder's crop and there are 40,000 such holdings covering an area of 80,000 ha (George and John, 1998). The cardamom-growing regions of South India lies within 8° and 30° latitude and 75° and 78° longitudes. The crop grows at elevations from 800 to 1500 m above mean sea level (amsl) and these areas lie on both, the windward and leeward, sides of the Western Ghats, which acts as a climate barrier of the monsoon trade winds, thereby determining the spatial distribution of rainfall. The rainfall pattern differs among the cardamom-growing regions located in Kerala, Karnataka, and Tamil Nadu (Nair *et al.*, 1991). The most important factor that has contributed to the increase in cardamom productivity is the cultivation of high-yielding varieties and improved crop management. However, cardamom export from India has plummeted during the same period. In 1985–1986, cardamom export was 3272 t while in 1989–1990 it touched a rock bottom level of 173 t—a steep decrease to 5.3%. In one decade, from 1985–1986 to 1994–1995, export earning came down from Indian Rupees (Rs) 53.46 crores to just Rs 7.6 crores, that is from US$11.9 million to US$1.8 million—a dramatic decrease of 85%.

1. Cardamom Cultivation in Other Parts of the World

The cultivation of cardamom is getting to be popular in certain pars of PNG. Cardamom grows here in virgin forestlands and its cultivation is exclusively with private estate owners. Productivity of these estates is very high, where yield levels of 2000–2500 kg ha^{-1} has been obtained (Krishna, 1997). Total production was about 313 million tons in 1985, which declined later to about 54 million tons in 1993. It hovers around 68–70 million tons. In Tanzania the crop was introduced in the beginning of the twentieth century by German immigrants and is being grown in certain parts of the country like Amani and East

Usambaras (Lawrence, 1978). The production was as high as 760 million tons in 1973–1974, but declined later to about 127 million tons in 1984–1985. This level continues even now. Sri Lanka is another small producer of the crop contributing about 75 million tons to world production annually.

Until early 1980s India was the leader in world cardamom production, when Guatemala came into the picture. From thereon India's production plummeted while that of Guatemala escalated. By the turn of the last century, while India's production came down by as much as 54% from the beginning of 1970s, that of Guatemala increased by as much as 199%. Guatemala is the major rival to India in cardamom production. A lot of Guatemalan cardamom is smuggled into India through the Nepal border which leads to the crash in Indian cardamom prices. As of now, nearly 90% of global cardamom trade is controlled by Guatemala. Among the many reasons, which adversely affected India's cardamom production, the following need to be noted (Table II).

1. Continuous drought, which lasts nearly half the year, combined with indiscriminate deforestation which leads to dramatic changes in the ecology of the cardamom habitat. Deforestation is the major cause of the dwindling of cardamom plantations.
2. Disease and insect pests' infestation.
3. The absence of superior crop management. For example, cardamom nutrition in India is still rooted in "textbook knowledge." Cardamom is a heavy feeder of potassium and the agronomists and soil scientists have not

Table II
Cardamom Scenario in Guatemala

Year	Area (ha)	Production (mt)	Productivity (kg ha^{-1})	Export (mt)
1985	32,336	7348.32	90.89	6173.50
1986	38,333	8845.20	92.33	7978.82
1987	41,418	10,591.56	102.29	11,489.69
1988	42,656	10,432.80	97.83	11,303.71
1989	43,000	11,340.00	105.49	11,076.91
1990	43,000	11,340.00	105.49	11,113.20
1991	43,000	12,201.84	113.51	13,163.47
1992	43,000	12,474.00	116.04	13,240.58
1993	47,472	12,927.60	114.57	14,442.62
1994	45,133	14,969.80	126.13	13,213.37
1995	47,472	15,603.84	131.48	13,920.98
1996	47,472	16,329.60	137.59	21,255.70
1997	119,540	16,692.48	139.64	14,020.78
Total	11,576.70			12,491.79

kept themselves abreast with advancements in crop nutrition. The relevance of the "The Nutrient Buffer Power Concept," especially with regard to potassium nutrition of cardamom, will be discussed in the following sections of this chapter.

4. Despite the aforesaid limiting factors, cardamom production in India has registered an increase due to enhanced productivity arising from the evolution of high-yielding clones, better crop management, and increased awareness of the importance of phytosanitary measures, especially control of diseases and pests. Between 1988–1989 and 1989–1990, cardamom export from India varied from 787 and 180 million tons, respectively. The export crossed the 500 million tons mark in 1991–1992 (544 million tons precisely) and it touched the 550 million tons mark in 1999–2000. During this period there was an increase in unit price from about Rs 125 (US\$3 kg^{-1}) in 1987–1988 to about Rs 395 (US\$9) in 1992–1993. In 1996–1997 the unit price was about Rs 384 (US\$8.9). The current unit price hovers around Rs 450 kg^{-1}, which is equivalent to about US\$10.5. The edge that Guatemala has over India is because of lower cost of production. This is the reason Guatemala edges out India in world cardamom trade. India has an extensive domestic market for cardamom. Annual consumption is around 7000 million tons. A survey indicates that it could be as high as 7300 million tons. And the total value of this market is close to Rs 2200 million, which is more than US\$50 million. This is, indeed, a large internal market. Apart from individual and household consumption, cardamom in India has an extensive industrial consumptive base. Manufacture of biscuits, cardamom flavored tea, and milk are some end uses for cardamom in the culinary sector apart from use in medicine manufacture of a herbal origin, food mixes, and the ubiquitous "pan masala" (the pervasive Indian "chewing gum," which leaves a pleasant flavor in the mouth). The industrial consumption of cardamom in India is estimated to be about 2050–2010 million tons annually, as of now. The demand in the hotel, bakery, and fast food sector is about 1250 million tons. In the current century, total demand of cardamom in India will escalate to about 9500 million tons annually (George and John, 1998).

II. CARDAMOM BOTANY

Cardamom belongs to the genus *Elettaria* and species *cardamomum* (Maton). The name is derived from the root Elettari, which in the popular South Indian language Tamil, means granules of leaf. The genus consists of about seven species (Mabberley, 1987). Only *Elettaria cardamomum*

(Maton) grows in India which is of economic importance. Closely related to *E. cardamomum* (Maton) is *E. ensal* (Gaertn) Abeywick. *E. major* (Thaiw.) is a native of Sri Lanka which is a much larger and sturdier plant. In Sri Lanka, it is known as the Sri Lankan "wild" Cardamom and it's flavor and taste are inferior to the Indian variety. *E. longituba* (Ridl.) Holtt., is the Malaysian variety, which is a large perennial herb and its flowering panicles often grow as tall as 3 m or more (Holttum, 1950), while the native Indian variety is a low grown one. Flowers appear singly, fruit is large and is not used. Seven species have been identified from Borneo (Indonesia) which have been listed by Sakai and Nagamasu (2000). The related genera are *Elettariopsis* and *Cypbostigma* and both genera occur in Malaysia–Indonesia region.

A. Taxonomy

Cardamom belongs to the monocot family Zingiberaceae (ginger family) of the natural order Scitaminae. Genus *Elettaria* consists of seven species which are distributed in India, Sri Lanka, Malaysia, and Indonesia. Among these only *E. cardamomum* is economically important (Holttum, 1950; Mabberley, 1987; Willis, 1967).

1. Type Species: *Elettaria cardamomum* (Linn.), Maton

a. Etymology. The generic epithet *Elettaria* is derived from Rheed's Elettari. Elathari (modern transcription of Rheed's name) is still used for the seeds of *E. cardamomum* (thari in local language means granules). Following is the description provided by Holttum (1950) of *Elettaria*.

> Stout or fairly stout rhizome, short intervals between leaf-shoots. Leaf shoots are tall with many blade-bearing leaves, while petioles are short and inflorescences arise from rhizome close to the base of a leaf-shoot. They are long, slender, prostrate, either just at the surface of the ground or just below it (not bearing roots), protected by alternate fairly large-scale leaves, in the axils of which cicinni arise, their attachment being sometimes supra-axillary. Cincinni short, bearing a close succession of tubular bracts, each of which encloses entirely the next flower and also the next bract; the flowers in two close rows on one side of the composite axis of the shoot, all pointing in the same direction, curved and opening in succession. Calyx tubular, split about one-fourth of its length down one side, shortly three-toothed; in some species joined at the base to the corolla-tube about as long as calyx; lobes not very broad, subequal, the upper one with a concave apex.

Labellum as in *Amomum*, with yellow median band and red stripes, sometimes so curved that it stands as a hood over the top of the flower. Staminodes none, or short and narrow. Filament of anther very short, broad. Anther longer than filament, stigma small, in close contact with the distal end of the pollen sac. Fruit globose or ellipsoid, thin-walled, smooth, or with longitudinal ridges when ripe.

Following is the description provided by Burtt and Smith (1983) *for E. cardamomum.*

Leafy shoot nearly 4 m high, petioles 2.5 cm, lamina about 1 m × 15 cm, lanceolate, acuminate, lightly pubescent or glabrous below; ligule about 1-cm long, entire. Inflorescence normally borne separately on a prostrate, erect or semierect stalk up to 40 cm long, or more in certain cases. Bracts two to three, 0.8–1.0 cm long, lanceolate, acute glabrous, rather persistent which becomes fimbriate with age. Cincinni many flowered. Bractioles about 2.5-cm long, tubular, mucronate, glabrous. Calyx about 2 cm long, 2 or obscutely 3-lobed, lobes mucronate. Corolla tube as long as calyx. Lobes 1–1.5 cm long, rounded at the apex, the dorsal tube widens. Labellum white, streaked violet, 1.5–2.1 cm at the widest part, ovate, obscurely 3-lobed, narrowed at the base. Lateral staminodes inconspicuous, subulate. Anther sessile, about 1 cm long, parallel, connective prolonged into a short, entire crest. Ovary 2–3 mm long, glabrous. Fruit is a capsule, oblong or more or less globose. The genus has only few species, the most important being *E. cardamomum* and *E. major* (*E. ensal*) from South India and Sri Lanka, respectively.

E. longituba Holttum (Syn. *E. longituba*) is one of the largest species of the genus grown in Malaysia. Its flowers appear singly at longer intervals and each cincinnus contains only few flowers. It appears that the cincinnus stops flowering as soon as fruit is formed. The fruits are large, but have no commercial value (Holttum, 1950). Sakai and Nagamasu (2000) in their studies on Bornean Zingiberaceae described six species of *Elettaria*, namely, *E. kapitensis, E. surculosa, E. linearicrista, E. longipilosa*, and *E. brachycalyx.*

2. Varieties

Based on the nature of panicles, three varieties of cardamom are recognized (Sastri, 1952; Table III). The variety Malabar is characterized by prostrate panicle and variety Mysore possesses erect panicle. The third

Table III
Varietal Description

Features	Malabar	Mysore	Vazhukka
Adaptability	Low Elevation (600–1000 m amsl)	High Elevation (900–1200 m amsl)	High Elevation (900–1200 m amsl)
Tolerance to drought	Withstands long dry spell (4–6 months)	Needs well-distributed rainfall	Needs well-distributed rainfall
Plant stature	Dwarf (2–3 m)	Tall (3–5 m)	Tall (3–5 m)
Leaf	Short petiole	Long petiole	Long petiole
Panicle	Prostrate	Erect	Semierect
Bearing nature	Early, short span of flowering	Late, long span of Flowering	Late, long span of Flowering
Capsule color	Pale, golden yellow	Green	Green

Source: Sudarsan *et al.* (1991).
Note: amsl: Above mean sea level.

variety Vazhukka is considered a natural hybrid between the two, and its panicle is semierect or flexuous.

a. Variety Malabar. Plants are medium sized and attain a height of 2–3 m on maturity. The dorsal side of leaves may be pubescent or glabrous. Panicles are prostrate and the fruits are globose, oblong shaped. It grows best at elevations of 600–1200 m amsl. It is less susceptible to the infestation of Thrips, a common cardamom pest. It can thrive under conditions of low rainfall.

b. Variety Mysore. Plants are robust and grow up to 3–4 m in height. Leaves are lanceolate or oblong-lanceolate, glabrous on both sides. Panicles are erect and the capsules are ovoid, bold, and dark green in color. They are better adapted to altitudes ranging from 900 to 1200 m amsl and thrive well under assured, well-distributed rainfall pattern.

c. Variety Vazhukka. This is a natural hybrid between both variety Malabar and variety Mysore and exhibit different characteristics which are intermediate to both these varieties. Plants are robust like variety Mysore. Leaves are deep green, oblong-lanceolate or ovate, panicles semierect (flexous) in nature and capsules are bold, globose, or ovoid in shape.

There are two more varieties, variety Mysorensis and variety Laxiflora, which have recognizable morphological characteristics.

d. Variety Mysorensis. A robust, tall plant that possesses either glabrous or pubescent leaves. This variety has flexous panicles. The flowers are produced in short racemes. The capsules are bold and distinctly three angled.

e. Variety Laxiflora. Comparatively less robust than variety Mysorensis, neither tall as the former. Leaves are glabrous with short petioles. This variety has flexuous, lax decumbent panicles. The flowers are produced in 4–40 short lax racemes. The capsules are variable, oblong–oblong fusiform.

In India, a number of other cultivars of cardamom are also recognized. In general, they can be considered as ecotypes of var. Mysore, var. Malabar, or var. Vazhukka. Most common among them are Bijapur, Kannielam, Makaraelam, Munjarabad, Nadan, and Thara.

f. The Sri Lankan Wild Cardamom (E. ensal Abheywickrama). The botanical identity of both the Sri Lankan wild cardamom and the Indian varieties described above is shrouded in much confusion. Cardamom varieties have been named differently by various authors as follows.

E. cardamomum var. minus
E. cardamomum var. miniscula
E. cardamomum var. major
E. cardamomum var. majus
E. cardamomum var. minor

Ridley (1912) who made one of the earliest descriptions of cardamom gives the following details. "There are two forms of varieties of the plant, viz., var. minus with narrower and less firm leaves and globose fruits from 0.5–0.1 in. long, grayish yellow or buff in color. This is confined to South India. Var. majus with shorter stems, broader leaves and oblong fruit, 1- to 2-in. long and rather narrower than the Malabar fruit, distinctly three sided, often arched and dark grayish brown when dry, the seeds larger and more numerous and less aromatic. This is the Ceylon cardamom and is peculiar to that country."

Owen (1901) in his notes on cardamom cultivation in Ceylon mentions three varieties, which he calls, the indigenous Ceylon, the Malabar, and Mysore. The first two can easily be recognized by the color of the stem. The Malabar plant is green or whitish at the base of the leafy or aerial stem, while in the Ceylon plant the base has a pink tinge. He also mentions that the Mysore form is robust, its panicles are borne perpendicularly from the bulbs and the fruits grow in clusters of five to seven. This form does well at high altitudes. *E. cardamomum* var. major was described earlier as *E. major* Sm. (Rees Cyclop., 39, 1819); but this name did not find favor with cardamom workers. Many subsequent authors used the terminology indiscriminately and even began mentioning var. Mysore as var. major. Abheyvickrama (1959) while studying the flora of Sri Lanka (Ceylon then) coined the name *E. ensal* for the Ceylon wild cardamom (from Zingiber ensal under

which the plant was described by Gaertner, 1791). But, Burtt (1980) is of the opinion that the differences are not reasons enough to differentiate this into a new species. However, Bernhard *et al.* (1971) and Rajapakse (1979) provided chemical evidence substantiating the distinct nature of Sri Lankan wild cardamom.

3. Fruit and Seed

The cardamom fruit is the one with great commercial value. The fruit is a capsule developed from an inferior ovary. It is more or less three sided with rounded edges. The shape and size vary. In var. Malabar, the fruits are short and broadly ovoid and dried fruits are somewhat longitudinally wrinkled. In var. Mysore, the fruits are ovoid to narrowly ellipsoid or elongate, the surface is more or less smooth. The wild Sri Lankan cardamom is much larger, elongate, angular, and distinctly three sided. The dry pericarp is about 0.5- to 1-mm thick having rough woody texture. The capsule has three locules, septa is membranous and placentation axile. There are five to eight seeds in each locule and they adhere together to form a mass. Transverse section of a pericarp shows outer and inner epidermis consisting of small polygonal cells and a mesocarp of thin-walled, closely packed, parenchymatous cells. Vascular bundles traverse the mesocarp; each bundle consists of a few xylem vessels, phloem, and a sclerenchymatous sheath partially surrounding the vascular elements. Many resin canal cells (oil cells) are found distributed in the mesocarp. The xylem vessels have spiral thickening. Some of the cells contain prismatic needle shaped calcium oxalate crystals. Cardamom seed has externally an aril composed of a few layers of thin-walled, elongated cells. In fully mature seeds, these cells contain small oil globules. The testa consists of an epidermis composed of elongated fusiform cells, about 250- to 1000-μ long, which in sectional view are nearly square, about 18-μ wide and 25-μ high (Wallis, 1967). A layer of small, flattened parenchyma cells are found below the epidermis. Below this there is a layer of large rectangular cells, about 18- to 120-μ long and 20- to 45-μ wide and high and these cells are filled with globules of volatile oil. Interior to this layer of large cells, there are two or three layers of small parenchymatous cells. The above layers of cells together form the outer seed coat. These layers get widened around the raphe where the vascular strand is surrounded by large oil cells. The inner seed coat consists of two layers, the inner one consists of heavily thickened polygonal cells about 15–25 μ in length and breadth and 30-μ high (Wallis, 1960). These cells are so thickened that only a small lumen is found at the upper end, in which there is a globule of silica, which nearly fills the cavity. The inner layer of the inner seed coat consists of a narrow band of thin-walled cells (Wallis, 1967). The kernel consists mostly of perisperm and a small

endosperm. The perisperm consists of thin-walled parenchymatous cells, which measure about 40–100 μm, each filled with such grains. One or two prismatic calcium oxalate crystals occur in each cell. The endosperm consists of thin-walled, closely packed, parenchymatous cells, 20–40 μm in length, which contain pale yellow-colored deposits. On iodine staining the contents turn deep blue, which shows the presence of starch. And these deposits turn red with Millons reagent, indicating the presence of proteins. The endosperm surrounds small, almost cylindrical embryo, which is made up of thin-walled cells. Parry (1969) as well as Trease and Evans (1983) also provide brief descriptions of the histology of cardamom seeds.

4. The Cardamom Powder

When cardamom seeds are powdered a grayish-colored powder with darker brown specks, which is gritty in texture and pleasant in smell and flavor, is obtained. The diagnostic character of cardamom powder is given by Jackson and Snowdon (1990).

1. With abundant starch grains, filling the cells of the periplasm, the individual starch grains are very small and angular and a hilum is not visible.
2. The sclerenchymatous layer of the testa, composed of a single layer of thick-walled cells which in a mature seed are dark reddish brown in color; each cell contains a module of silica.
3. Abundant fragments of the epidermis of the testa, composed of layers of yellowish brown, parenchymatous cells, with moderately thickened pitted walls.
4. The oil cells of the testa consisting of a single layer of large polygonal rectangular cells with slightly thickened walls and containing globules of volatile oil. This layer is found associated with the epidermis and hypodermis.
5. The parenchyma of the testa composed of several layers of small cells polygonal in surface view, with dark brown contents and slightly thickened heavily pitted walls.
6. The abundant parenchyma of the perisperm and endosperm composed of closely packed, thin-walled cells.
7. The fragment of the arillus is composed of thin-walled cells; elongated and irregularly fusiform in surface view.
8. Calcium oxalate crystals, prismatic in shape, are found scattered in the cells of the perisperm and other cells.

9. Infrequently groups of xylem vessels are visible, which have spiral thickening, associated with thin-walled parenchyma.

The type of cardamom can be determined by counting the number of heavily thickened sclerenchymatous cells per square millimeter of a layer and using standard figure for each type as follows:

Mysore: 3310
Alleppey Green: 3790
Malabar: 4600

The above-mentioned classification has been given by Wallis (1967). The Sri Lankan wild cardamom contains 3020 sclerenchymatous cells per millimeter of layer.

5. Growth, Flowering, and Fruit Set in Cardamom

As time passes, tillers emerge from the axils of underground stem and from their bases vegetative buds emerge throughout the year. However, majority of the vegetative buds are produced between January–March. Linear growth of tiller increases with the onset of the southwest monsoon, the principal rainfall, in India and once the rains cease growth slows down. Linear growth pattern of tiller is similar in all cultivars. It takes almost 10 months for a vegetative bud to develop and about a year to panicle emergence from newly formed tillers (Sudarshan *et al.*, 1988). A round the year study on the phenology of tiller and panicle production in three varieties of cardamom was carried out by Kuruvilla *et al.* (1992a). Panicles emerge from swollen bases of tillers. Generally, two to three panicles emerge from the base of a tiller. Detailed investigation on panicle production, growth, and duration of flowering has been carried out by Pattanshetty and Prasad (1976) and Parameswar (1973). Vegetative shoots acquire maturity in about 10–12 months to produce reproductive buds and the newly emerging panicles take a period of 7–8 months to complete growth. With the onset of monsoon, flowering in cardamom commences. Flowering pattern depends on the region's agroclimatic characteristics and the cultivars in question. Flowers appear on the panicles after 4 months and flowering continues during the next 6 months. These panicles grow either erect (var. Mysore), prostrate, and parallel to the ground (var. Malabar), or in a semierect (flexous) manner in var. Vazhukka. Each inflorescence (panicle) possesses a long cane-like peduncle having nodes and internodes. Each node has a scale leaf in the axil of which flowers are borne on a modified helicoids cyme (cincinnus). Thus, the panicle is branched. Multiple branching of panicles occurs in certain cultivars. In such cases, the central

peduncle branches further into secondary and tertiary branches producing multibranched panicles. Such branching can either present at the lower part of the main peduncle or top part alone or throughout the peduncle. Panicles bear leafy bracts on nodes and flowers are produced in clusters (cincinnus) in the axils of bracts. Earlier researchers on cardamom described the cluster of flowers as raceme, which is incorrect. Each cluster is a cincinnus (Holttum, 1950). A cincinnus is a modified helicoid cyme. Approximately it takes 90–110 days for the first flower to emerge in fresh panicle, irrespective of the variety. The cincinni and capsules are formed during their fourth and fifth months, respectively after the initiation of the panicle (Kuruvilla *et al.*, 1992). Capsule formation increased until August (Table IV) and thereafter declined slowly. The flowers have the typical morphology of zingiberaceous flower. Flower opening commences from 3.30 A.M. in the early morning and continues until 7.30 A.M. Between 7.30 and 8.30 A.M. anther dehiscence takes place. Flowers invariably wither in a day. Normally flowering is seen round the year on panicles produced during the same year as well as on panicles produced in the previous year. Flowering is spread over a period of 6 months, from May through October, in India when the majority of cardamom plantations still are in the southwest monsoon period. It is during June–August that almost 75% of the flowers are produced. The time required to reach full bloom stage from flower bud initiation stage ranges from 25 to 35 days and capsules mature in about 120 days from the full bloom stage (Krishnamurthy *et al.*, 1989a).

Table IV
Development and Pattern of Growth of Panicles

	Malabar			Vazhukka			Mysore		
Month	A	B	C	A	B	C	A	B	C
January	3.76	–	–	6.77	–	–	4.83	–	–
February	6.34	–	–	9.20	–	–	7.23	–	–
March	7.91	–	–	12.50	–	–	11.0	–	–
April	11.85	–	–	13.02	–	–	16.60	–	–
May	17.52	13.63	–	22.76	11.06	–	23.50	14.93	–
June	18.80	14.93	18.56	23.73	14.70	4.20	23.66	17.13	14.06
July	18.40	15.40	34.30	22.13	15.73	8.16	21.30	16.13	21.86
August	17.63	15.93	39.23	18.86	11.36	8.13	23.66	16.76	29.70
September	18.40	13.76	31.23	16.46	9.83	3.96	24.36	16.63	19.93
October	18.52	14.71	3.81	25.07	14.40	2.60	24.96	16.15	11.15
November	18.41	14.43	1.52	25.20	14.40	0.67	25.11	16.07	3.74
December	18.90	14.44	0.33	25.87	14.20	0	25.44	16.07	0.48

Source: Kuruvilla *et al.* (1992a).
Note: A, panicle length (cm); B, number of cincinni; and C, number of capsules.

6. Palynology and Pollination Biology

The pollen grains of cardamom plants are rich in starch and while shedding are two celled. Moniliform refractive bodies can be seen in some pollen grains. Exine develops warty projections that are spinescent (Panchaksharappa, 1966). Pollen fertility is maximum at full bloom stage and low at the commencement and cessation of flowering periods Parameshwar and Venugopal (1974). Pollen grain size varies from 75 to 120 μ in different varieties, and they lose their viability quickly. After 2 h only 6.5% are viable and after 6 h of storage none (Krishnamurthy *et al.*, 1989). During early and later stages of flowering pollen fertility tends to decline. They germinate in 10% sucrose solution, and addition of 200 ppm boric acid enhances germination and tube growth (Parameshwar and Venugopal, 1974). Kuruvilla *et al.* (1989) found that 15% sucrose and 150 ppm boric acid favored pollen germination and tube growth at an ideal temperature of 15–20°C; 5–10 ppm of coconut water, GA, Cycocel and Ethrel enhanced pollen germination and tube growth significantly.

Cardamom plants have bisexual flowers. Pollen and stigma are so placed within the flower that without an external intervention pollination cannot take place. Honeybees (*Apis cerana, Apis indica*, and *Apis dorsata*) visit cardamom plantations during flowering stage to collect nectar and pollen, and they conduct over 90% pollination. Stigma remains receptive from 4 A.M. on the day of flowering and the receptivity is maximum between 8 A.M. and 12 P.M. (Krishamurthy *et al.*, 1989a, Kuruvilla and Madhusoodanan, 1988). Peak pollen activity was noticed around noon (Belavadi *et al.*, 1998; Parvathi *et al.*, 1993), and this coincided with peak pollination. A detailed study of pollination in cardamom in PNG has been carried out by Stone and Willmer (1989). There the most common foragers are *Apis mellifera* and to some extent *Apis sapiens*. Over time *Apis mellifera* was seen to show changes in pollen-foraging activity. Foraging commences around 7 A.M., peaks at around 10 A.M. By 12.30 P.M. pollen activity declines substantially, and by this time the majority of stigmas get pollinated.

Interesting observations on flower structure and pollination by honeybees have been made by Belavadi *et al.* (1977). In cardamom flowers nectar is present in the corolla tube which is 23 ± 2.08 mm long (21.48- to 30.4-mm range), through which the style passes. The honey bees (*Apis cerana* and *Apis dorsata*) despite their short tongue lengths (14.5 and 5.5 mm, respectively) drew nectar up to 11.45 ± 2.65 and 11.65 ± 1.85 mm, respectively. Controlled experiments using capillary tubes of similar dimensions showed that the depth of feeding by the two bee species corresponded to their tongue length when there was no style. When a style was introduced, the depth of feeding increased with increase in style thickness. The presence of a style inside the corolla tube helped bees to draw more nectar from the cardamom flowers. Mean number of flowers per bush which open per day is 34.5.

Mean proportion of flowers per bush visited by each *Apis mellifera* and is 25%, independent of the number of flowers present on a plant and the time of the day. Hence, the mean number of flowers visited is only 8.6. Pollen production per flower is reported to be 1.3 ± 0.2 mg, and this quantity gets diminished to 0.6 ± 0.2 mg after the visit of a bee, indicating that during the first foraging about 50% of the pollen is removed. Cardamom nectar contains 55–100 mmol liter^{-1} of glucose and is neutral in reaction. The amino acid concentration at 8 A.M. is 3 mM. Over time nectar volume varies greatly. Initial volume at dawn was about 1.6 μl and by 11 A.M. this increases to about 209 μl. This increase is due to the active secretion by the nectaries at the base of the corolla tube. Nectar volume drops rapidly following foraging by a bee (Stone and Willmer, 1989). In one location in PNG, the number of *Apis mellifera* visiting each flower was 31 times a day, while in another location, the average visit was only 10.3 times a day. In the former area fruit set was much higher. Bee-pollinated fruits were found to contain on average 11 seeds per capsule (Chandran *et al.*, 1983) in South India, while in PNG on average they were 13.8 per capsule. Belavadi *et al.* (1993, 1997, 1998), Parvathi *et al.* (1993), Belavadi and Parvathi (1998) have carried out detailed studies on pollination ecology and biology of cardamom in a cardamom-cropping system in Karnataka in South India. The pollination activity here starts around 7.30 A.M. in the morning and continues until 6.30 P.M. in the evening, while it peaks between 11 A.M and 13.00 P.M. The bees appear on cardamom clumps when the temperature is around 21°C. Individual foragers of *Avis cerana* made four to seven trips to a single patch of flowers in a day and the number of flowers visited on each successive trip progressively increased. In a day individual foragers visited 157–514 flowers a day. A flower is visited as many as 120 times on a clear sunny day, 57 times on a cloudy rainy day and, on average, 20 times a day. Mean number of flowers visited by a bee at a given clump is 12.32, when mean number of flowers per clump is 30. The number of honey bee colonies required for effective pollination in cardamom has also been calculated by the aforesaid workers. For 3000 plants ha^{-1} planted 1.8 m apart, there will approximately be 60,000 flowers for effective pollination a day. Based on the pollinator activity a minimum of three colonies per hectare is needed, assuming that a colony will have about 5000 foragers. An isolation distance of 15 m for seed production has been suggested, based on pollinator activity, for seed production (Belavadi *et al.*, 1993).

7. Fruit Setting

When ripe, cardamom fruit is globose or ellipsoid, thin walled, smooth or with longitudinal ridges. Fruit shapes indicate varietal variations. Fruit is

green colored which turn golden yellow on ripening. Seeds are white when unripe and turn brown on aging and become black on maturity and their numbers per capsule vary between 10 and 20 depending on genotypes. A thin mucilaginous membrane (aril) covers the seeds. Extent of fruit set is highest when atmospheric humidity is very high in the cardamom region, while it is scanty in summer months, even when the crop is irrigated. This clearly indicates that the crop thrives best in a cool, overcast climate. In general, percentage of fruit set is high among young plants and when plants overshoot the economic life span, fruit set declines to 50% or even more.

8. Physiology of Cardamom

a. Photosynthesis. Among the growth parameters, total leaf area (TLA) is closely associated with photosysnthesis and dry matter production. Hence, a precise estimation of TLA and canopy density are important to estimate productivity. Korikanthimath and Rao (1993) reported a reliable method for TLA estimation based on linear measurements of intact leaves followed by appropriate regression analysis. There were varietal differences in the TLA factor. The light fraction that the leaves absorb has a direct bearing on crop growth and canopy development. Laboratory studies on photosynthetic efficiency in cardamom (cvs. PV-19 and PR-107) indicated that efficiency was greater at low light intensities than at higher ones. Low light compensation point favors photosynthesis. Translocation pattern showed that rhizome was the major sink followed by panicle and roots. Unlabelled leaves did not receive much of the labeled photosynthates from labeled leaves (Vasanthakumar *et al.*, 1989). Kulandaivelu and Ravindran (1982) studied the photosynthetic activity of three cardamom genotypes, measured at the rate of oxygen liberated by isolated chloroplasts. Results showed drastic reduction in photosynthetic rates in plants exposed to warm climate. As much as 60–80% decrease in the level of total chlorophyll was noticed in all the three varieties tested. Light requirements for cardamom nursery is approximately 50% of the normal (Ranjithakumari *et al.*, 1993), and the growth and production of tillers is best at this light intensity.

b. Effect of Growth Regulators on Cardamom Fruit Setting. In cardamom a high percentage of flowers are shed before they reach maturity, nearly 80% of fruit drop (Parameshwar and Venugopal, 1974). Temperature, wind, humidity, nutritional deficiencies, physical injuries, competition for resources, soil fertility, incidence of pests and diseases, and so on affect fruit set and fruit drop (Kuttappa, 1969a).

In cardamom growth regulators are important for proper fruit set. Table V gives the effect of NAA, GA, and 2,4–8 on fruit set and fruit weight

Table V
Growth Regulators and Fruit Set

Treatment		Mean fruit set (%)	Fruit weight (g)
Control		43.20	0.80
NAA	25 ppm	60.75	0.85
	50 ppm	61.62	0.83
	75 ppm	67.04	0.71
GA	25 ppm	37.72	0.78
	50 ppm	48.73	0.83
	75 ppm	54.11	0.90
2,4-D	2.5 ppm	69.80	0.80
	5.0 ppm	65.12	0.79
	7.5 ppm	47.56	0.82
LSD ($p = 0.05$)		10.69	N.S
LSD ($p = 0.01$)		14.18	–

Source: Krishnamurthy *et al.* (1989b).
Note: LSD, least significant difference; N.S., not significant.

(Krishnamurthy *et al.*, 1989b). Significant differences could be noticed in the case of fruit set. Tissue concentration of auxins was highest 36 h after pollination at 315 mg g^{-1} of tissue, which further declined to 80 mg g^{-1} 30 days after pollination. The fall in auxin activity resulted in the formation of an abcission zone resulting in the shedding of immature capsules. Application of 40 ppm NAA or 4 ppm of 2,4–8 decreased the capsule drop which also led to an increase in yield (Vasanthakumar and Mohanakumaran, 1988). Gibberellic acid (GA) at 25, 50, 100, 150, 200, 250, and 300 ppm and 2,4–8 at 2–5 ppm and 10 ppm were sprayed on cardamom plants and the response was monitored, which showed increased panicle length, especially with GA at 50 ppm and the maximum fruit set was observed at 200 ppm spray (Pillai and Santha Kumari, 1965). Indole acetic acid (IAA) and indole butyric acid (IBA) failed to enhance fruit set (Nair and Vijayan, 1973). Siddagangaih *et al.* (1993) investigated the effect of chloromequat, daminocide, ethepon, and malic hydrazide (250 ppm). Daminozide (1500 ppm), chloromequat (250 ppm), and ethepon (100 ppm) significantly enhanced tiller production and other vegetative characters when applied on 7-month-old seedlings, but had little effect on other morphological characters.

c. Effect of Moisture Stress on Cardamom Yield. In South India, both Kerala and Karnataka states, where cardamom is extensively grown, experience drought for about 4–5 months in a year. Large-scale yield losses are observed due to drought in Idukki, Palakkad, and Waynad districts of Kerala State where cardamom is extensively grown. To enhance cardamom

productivity in India, identification of cardamom genotypes tolerant to moisture stress is an important prerequisite. At the Regional Cardamom Research Station in Mudigere, in Coorg district of Karnataka State, cardamom genotypes were screened to select clones possessing drought tolerance traits. Clones differ in their drought susceptibility. As a reliable parameter for drought tolerance, chlorophyll stability index (CSI) was investigated by Krishnamurthy *et al.* (1989a) of three prominent varieties, Malabar, Mysore, and Vazhukka (described previously). For purpose of comparison, related taxa, namely, *Hedychium flavescence* and *Amomum subulatum* were also investigated. Malabar had the highest CSI (43.14) and Mysore had the lowest CSI (24.5), and Vazhukka was intermediate (31.14). CSI is expressed as percent. Electrolyte leakage was highest (66.65%) in Mysore, 69.42% in Vazhukka, and 43.90 per cent in Malabar. These results clearly indicate the inverse relationship between CSI and electrolyte leakage among the varieties, pointing to the important fact why Malabar outperforms both Mysore and Vazhukka varieties.

Among the other physiological parameters, dry matter accumulation (DMA) and harvest index (HI) are important in helping breeders in their breeding program for cardamom improvement. Dry matter accumulation during drought spells over a 3-year period has been investigated by Krishnamurthy *et al.* (1989a). The authors investigated a number of cardamom clones and found significant variations among them. DMA during the drought period of March–June varied from 161 g per plant to 279.5 g per plant. At the end of the drought spell (June) DMA ranged from 195 g per plant to 391 g per plant. It was observed that those clones, which had the highest DMA, also had the maximum leaf area index (LAI), another yield-determining physiological parameter. Korikanthimath and Mulge (1998) investigated the various vegetative and physiological parameters in 12 clones planted in the "Trench System"—a specialized pattern of planting where the trenches measure 1.8 m $\times$ 0.6 m. These authors measured dry matter content of roots, rhizome, panicles, capsules, tillers, and leaves, which they found varying significantly among the clones. Total dry matter varied from 2759 to 4853 g. Dry matter in capsules varied from 13.2 to 234.3 g. Harvest index varied from 0.06 (native variety) to 0.091 a "selection" (clone). Partitioning of photosynthates within the plant is governed by genetic variability. This reflected in the DMA in capsules. These investigations help the breeders to target high productivity in cardamom.

B. Crop Improvement

Cardamom-crop productivity can be enhanced by, first, use of high-yielding genetic materials, and second, improved crop and soil management practices. The major constraints to cardamom productivity are the lack of

superior yielding genotypes, onslaught of drought and devastation by insect pests and diseases. Inasmuch as the first factor is concerned, availability of germplasms with high-yield potential, superior capsule quality, and wide adaptability are the three criteria affecting productivity. Selection of clones, which possess resistance/tolerance to major pests and diseases as well as drought, should be the priority area for the crop-breeding program.

1. Germplasm

Since cardamom is a cross-pollinated crop which is propagated mostly by seeds, natural variability is fairly high. Assembling a wide range of genetic stock, which forms the basis for further breeding or selection work, is the first step in moulding new varieties for use by farmers and end users. Hence, collection, conservation, evaluation, and exploitation of existing germplasm deserve utmost importance in breeding strategies. In the 1950s, in India, two surveys were conducted in cardamom-growing regions to record genetic resources and wild populations (Mayne, 1951a) and to understand the geographical distribution and environmental impact on cardamom (Abraham

Table VI
Spread of Cardamom Germplasms in India

Center	Germplasm under cultivation	Wild and related taxa
Regional Research Station of the Indian Institute of Spices Research (IISR), Appangala, Coorg district, Karnataka State, India, under the administrative control of the Indian Council of Agricultural Research, New Delhi, India	314	13
Indian Cardamom Research Institute, Myladumpara, Idukki district, Kerala State, India, under the administrative control of The Ministry of Commerce, Government of India	600	12
Cardamom Research Center, Pampadumpara, Idukki district, under the administrative control of the Kerala Agricultural University, Thrissur, Kerala State, India	72	15
Regional Research Station, Mudigere, Chickmagalur district, Karnataka State	236	7

and Thulasidas, 1958). This was the first organized attempt in India to catalog the cardamom crop. Thereafter, explorations for germplasm collection have been made by six research organizations in the country and the total number of accessions presently available at different research centers are 1350 (Madhusoodanan *et al.*, 1998, 1999; Table VI). Earlier documentation was based on an old descriptor (Dandin *et al.*, 1981) and a key for identification of various types has been formulated (Sudarshan *et al.*, 1991). During 1994, a detailed descriptor for cardamom was brought out by the International Plant Genetic Resources Institute (IPGRI), in Rome, Italy. Among the collections, genotypes having marker characters include terminal panicle, narrow leaves, pink-colored tillers, compound panicles, elongated pedicel, and so on. Asexuality, cleistogamy, and female sterility are a few of the variations observed among the collections. Conservation of cardamom genetic resources under *in situ* conditions does not exist, although natural population occurs in protected forest areas, especially in the world-famous "Silent Valley Biosphere Reserve" in Kerala State, where a sizeable population of cardamom plants in its natural habitat exists. Many organizations are now undertaking *ex situ* conservation of cardamom. The following table details holdings in these centers.

2. Genetic Variability in Cardamom

The accessions of cardamom germplasm available at the Regional Research Station, Mudigere, have been classified by Krishmurthy *et al.* (1989). Based on leaf pubescence, height and color of aerial stem, panicle type, and so on, there are 26 distinct types. A study to assess the variability among 210 germplasms assembled from all major cardamom-growing regions at the Cardamom Research Center, Appangala, was carried out by Padmini *et al.* (1999). These observations indicated that, in general, var. Vazhukka and var. Mysore are more robust than var. Malabar. The total numbers of tillers as well as bearing tillers per plant, leafy stem diameter, and number of leaves are more in var. Vazhukka and var. Mysore than in var. Malabar. The mean number of panicles per plant is higher in var. Malabar than in the other two. Plant characters, such as panicle number, nodes per panicles, internode length, and capsule length, exhibited high coefficient of variation (Padmini *et al.*, 1999). Among the Malabar accessions, coefficient of variation percentage was highest for the number of panicles per plant. In var. Mysore the character having the highest variability is panicle per plant, and internode length of panicle. In var. Vazhukka the highest coefficient of variation was recorded for panicles per plant followed by the number of bearing tillers per plant.

Observations on natural variations in morphological and yield parameters under the cardamom-growing situation in Idukki district of Kerala State were recorded by George *et al.* (1981). Highest variability was observed with regard to panicle characters (Anon, 1958, 1986a,b,c, 1987). George *et al.* (1981) collected 180 accessions from the wild as well as from cardamom-growing regions of the Western Ghats of Kerala State. They isolated distinct morphotypes and 12 ecotypes showing heritable adaptations. They observed that var. Mysore and var. Vazhukka were more vigorous than var. Malabar attaining a height of nearly 6 m. One clone had very narrow leaves, 3-cm wide. In two accessions tillers had characteristic pink and pale green colors. In general each tiller had two panicles and accessions having three or four panicles per tiller were present especially among the Munzerabad clones. Another known as "Alfred clone" produced both basal and terminal panicles. Panicle length was highly variable among accessions, ranging from 30 to 200 cm, mean being 140 cm in var. Mysore and var. Vazhukka and 80 cm in var. Malabar. Some accessions produced multiple branched panicles. Number of flowers/fruit varied from 4 to 36 per cincinnus. Variations were noticed in fruit shape as well. Plants having multibranched panicles or compound panicles occur in small proportions in the segregating populations of certain lines. Padmini *et al.* (2000) investigated the variability among compound panicle types, which have, mostly, var. Vazhukka type inflorescence. Among the compound panicles, proximal branching is more prevalent than the distal or entire branching types. The contribution of such branching toward yield (weight of fresh and dry capsules) varied from 12 to 41%. Branching did not influence other yield or quality characters.

3. Genetic Upgradation of Cardamom

Cardamom can be propagated both sexually and asexually through vegetative cuttings. Techniques, such as selection, hybridization, mutation, and polyploid breeding, are used as means of genetic upgradation of the crop. Studies on certain aspects of crop improvement in cardamom have also been carried out in Sri Lanka (Melgode, 1938), Tanzania (Rijekbusch and Allen, 1971), Guatemala (Rubido, 1967), and Papa New Guinea (Stone and Willmer, 1989).

4. Selection

There are definite breeding pathways in cardamom selection especially with regard to clonal selection. Gopal *et al.* (1990, 1992) have carried out extensive correlation and path analysis which showed that the dry weight of capsules per plant was positively correlated with the other polygenic characters like tiller

height (“*r*” = 0.88), productive tillers per plant (“*r*” = 0.78), panicles per plant (“*r*” = 0.998), capsules per panicle (“*r*” = 0.998), fresh weight of capsules per plant (“*r*” = 0.99), length of panicles (“*r*” = 0.87), nodes per panicle (“*r*” = 0.96), and internodal length of panicle (“*r*” = 0.63). Number of panicles per plant, fresh weight of capsules per plant, nodes per panicle, and internodal length of the panicle showed statistically significant positive direct effects on yield. Panicles per plant showed maximum direct effect on yield followed by fresh weight of capsules per plant. The above workers concluded that panicles per plant, fresh weight of capsules per plant, nodes per panicle and internodal length of panicle were useful characters for improvement of cardamom yield. Patel *et al.* (1997, 1998) have also suggested the use of such traits like panicles per bearing tiller, panicles per clump, recovery ratio and capsules per panicle as the important criteria for selection for cardamom yield. In a study using 12 genotypes these researchers found that yield per clump had significant and positive correlation with capsules per panicle (“*r*” = 0.967), cincinni per panicle (“*r*” = 0.645), tillers per clump (“*r*” = 0.639), panicle length (“*r*” = 0.559), panicles per clump (“*r*” = 0.537), bearing tillers per clump (“*r*” = 0.340), vegetative buds per clump (“*r*” = 0.309), and recovery ratio (“*r*” = 0.224). Negative correlation was observed between fresh yield per clump and dry capsules per kg (“*r*” = –0.486). These researchers concluded that capsules and cincinni per panicle, bearing tillers and panicles per clump, panicle length, and vegetative buds per clump are significant attributes primarily responsible for high yield of cardamom, and selection for yield improvement should be based on these attributes (Patel *et al.*, 1997, 1998). Systematic evaluation of germplasm accessions in India during the 1980s resulted in the identification and release of some elite clonal selections (Table VII). Initial collection for desirable traits were made from planter’s fields as well as from wild habitats based on certain parameters. In order to isolate elite clones, germplasm collections were subjected to initial evaluation trials followed by comparative yield trials and multilocation tests in various agroecological situations. Few studies only were taken up for selection of seedlings having precocity in bearing. Results indicate that this phenomenon has no positive bearing on yield (Madhusoodanan and Radhakrishnan, 1996). Selection for drought tolerance has also been attempted. Initial results indicate that those genotypes tolerant to drought are low yielders.

a. Selection for Biotic Stress Tolerance. At the Cardamom Research Center, Appangala, Karnataka State, under the administrative control of the Indian Institute of Spices Research, Calicut, Kerala State, a survey was conducted to collect disease escapes from the hot spot areas of the devastating “Katte” disease of cardamom. Collections of natural katte escapes (NKE) lines from such surveys were then subjected to artificial inoculation through the use of insect vectors. The plants that have not taken up infection

Table VII
Elite Selections of Cardamom

Selection	Plant type	Average yield (kg ha^{-1})	Oil (%)	Distinguishing features
Mudigere-1	Malabar	275	8	Compact plant suited for high-density planting. Tolerant to hairy caterpillars and white grubs. Short panicle, oval and bold pale green capsules, leaves pubescent.
Mudigere-2	Malabar	476	8	Round capsule, suited to hilly zones of Karnataka State
PV-1	Malabar	260	6.8	Early maturing variety with slightly ribbed, light-green capsules. Short panicle, close cincinni, elongated capsules
CCS-1 (IISR “Suvasini”)	Malabar	409	8.7	Early maturing variety suitable for high-density planting. Long panicle, oblong, bold, parrot-green capsules
ICRI-1	Malabar	656	8.3	Early maturing, profusely flowering variety. Long panicle, globose, extrabold, dark green capsules
ICRI-2	Mysore	766	9.0	Performs well in irrigated conditions. Suitable for high altitude planting. Long panicle, oblong, bold, and parrot-green capsules
ICRI-3	Malabar	599	6.6	Early maturing, nonpubescent leaves, oblong, bold, parrot-green capsules
BRI (IISR “Avinash”)	Malabar	960	6.7	Selection from hot-spot areas. Resistant to Rhizome rot disease
TDK-4	Malabar	456	6.4	Suitable for low-rainfall area, highly adapted to lower Pulney hills of Tamil Nadu State
PV-2	Malabar	982	10.45	Selection from OP seedling progeny ofPV-1. Early maturing, bold capsules, high dry recovery, tolerant to Thrips
IISR “Vijeta” (NKE-12)*	Malabar	643	7.9	Suited to highly shaded, mosaic disease areas, Oblong capsule, virus resistant
Farmer’s Selection “Njallani Green Gold”**	Vazhukka	–	–	Clonal selection by a Cardamom grower in Idukki district of Kerala State. High yielding, bold capsules, More than 70% of cured cardamom above 7 mm in size

*Yield up to 1600 kg ha^{-1} in farmer’s fields.
**Yield up to 2475 kg ha^{-1} in farmers fields.

even after continued screening were field evaluated again in a hot spot area. Some of the selections are good yielders, and with good quality, comparable with those already released for cultivation. One specific collection, RR-1 gave highest yield and was found to be resistant to the rhizome rot caused by *Phytopthora* sp. The yield is comparable with NKE lines. Further studies and improvement of the NKE lines was accomplished using the diallell crossing technique (IISR, 1998).

b. Selection for Drought Tolerance. For drought tolerance studies on cardamom selections, parameters, such as relative water content, membrane leakage, stomatal resistance, and specific leaf weight, have been used as important criteria among cultivars (IISR, 1997).

c. Hybridization. The popular cardamom variety Vazhukka possibly originated as a natural cross between var. Malabar and var. Mysore. Since cardamom can be propagated both by sexual and vegetative methods, hybridization is a very useful tool for crop improvement. As only one species of cardamom occurs in India, crossing in cardamom is confined to intraspecific levels. On account of its perennial, crosspollinated, heterozygous nature, the conventional methods for evolving homozygous lines in cardamom are time consuming.

Both intergeneric and intervarietal hybridizations have been carried out by various cardamom researchers. The former method was tried with the objective of transferring disease resistance. Such attempts have not borne encouraging results, except in the case of fruit set in a cross with *Alpinia neutans* (Parameswar, 1977). All other intergeneric crosses involving *Amomum, Alpinia, Hedychium*, and *Aframomum* were sterile (Krishnamurthy *et al*., 1989a; Madhusoodanan *et al*., 1990). Intervarietal and intercultivar hybridizations have been carried out to produce high-yielding heterotic recombinants. A diallel cross involving six related types having characters of early bearing, bold capsule, high yield, long panicle, leaf rot resistance, and multiple branching was carried out and 30 cross combinations were made. All the resulting hybrids were more vigorous than the parental lines (Krishnamurthy *et al*., 1989a). In another study, intervarietal hybridization has been carried out using different varieties of cardamom. This has resulted in cross-combinations of 56 F1 hybrids. Evaluation of these hybrids led to the isolation of a few high-yielding heterotic recombinants having an average yield of 470–610 kg ha^{-1} under moderate management (Madhusoodanan *et al*., 1998, 1999).

d. Selection Among Polycross Progenies. The impact of selection in a polycross progeny population was investigated by Chandrappa *et al*. (1998). Promising clonal selection of var. Malabar, including the prominent variety Mudigere-1, were grown in isolation and open pollinated varieties of these selections were evaluated. In the case of 34% of the progenies, average yield

was found to be significantly higher than the average yield of the control variety, Mudigere-1. This yield increase varied from 1 to 149% and promising clones were 691, 692, D11, and D19. The above-mentioned researchers found that cardamom yield improvements could be more effectively achieved through a polycross breeding program. Compared to the highest yield per plant of 1663 g, expected in the progenies of Mudigere-1, one selection from polycross seeds of Mudigere-1 yielded 2360 g per plant, which is 44% higher and another progeny from the line D 237 gave 2670 g per plant yield which represents 60% higher yield compared to the highest yield observed in the progeny of Mudigere-1. The same researchers found that based on the polycross progeny test, 38% clones were poor in combining ability, which can be rejected. They further suggested that lines with better combining ability, such as Mudigere-1, Cl-691, Cl-692, D-11, D-18, D-19, D-186, D-535, and D-730, yielded 46–149% higher compared to the means of the polycross progeny and the checks could be used to establish restricted polycross nursery to isolate higher yielding selections. The authors had investigated a population more than 3000 plants.

e. Polyploidy. Polyploids ($2n = 4x = 96$) were successfully induced in cardamom by treating the sprouting seeds with 0.5% aqueous solution of colchicines (Sudarshan, 1987, 1989). The polyploid lines exhibited gigantism. Increased layer of epidermal cells, thicker cuticle, and higher wax coating on the leaves found in the induced polyploid lines are characters generally associated with drought tolerance in nature. The meiotic behavior of induced polyploids was almost normal and they had reasonably good fertility. In all yield characters the tetraploids were reported to be inferior to the diploids (Anon, 1986).

f. Mutation Breeding. Attempts for induction of desirable mutants using physical mutagens, namely, X-rays and γ-rays (Co60 source) and chemical mutagens (ethyl methane sulphonate and maleic hydrazide) have been made. Of the large number of selfed and open pollinated progenies of M1 plants, which did not take infection after repeated cycles of inoculations with Katte virus vector, 12 plants were selected as tolerant to the disease (Bavappa, 1986). There are reports on sterility (Pillai and Santha Kumari, 1965) and absence of macromutation in M1 generation and its progeny (Anon., 1987). No desirable mutant could so far be developed in cardamom.

g. Biotechnology

1. Microporopagation
   a. The technique of micropropagation offers the best scope for rapid vegetative propagation of elite clones or varieties, eliminating systemic pathogens such as viruses (Table VIII). Replanting of senile, seedling-raised plantations with selected high-yielding clones multiplied

Table VIII
Tissue Culture in Cardamom

Explant	Media composition	*In vitro* response	References
Vegetative bud	MS + 1 mg liter^{-1} BA 0.5 mg liter^{-1} NAA	Multiple shoots, *in vitro* rooting	Nirmal Babu *et al*. (1997a)
	MS + 0.5 mg liter^{-1} BA 0.5 mg liter^{-1} kinetin, 2 mg liter^{-1} Biotin, 0.2 mg liter^{-1} calcium pantothenate, 5% coconut milk	Multiple shoots, *in vitro* rooting	Nadgauda *et al*. (1983)
Rhizome of TC plants	MS + 1 mg liter^{-1}l 2,4–8 0.1 mg liter^{-1} NAA, 7 mg liter^{-1} BA, 0.5 mg liter^{-1} kinetin	Callus	Lukose *et al*. (1993)
Immature panicles	MS + 0.5 mg liter^{-1} NAA 0.5 mg liter^{-1} kinetin, 1 mg liter^{-1} BA, 0.1 mg liter^{-1} calcium pantothenate, 0.1 mg liter^{-1} folic acid, 10% coconut milk	Conversion of floral primordium into vegetative buds	Kumar *et al*. (1985)
Callus derived from vegetative buds	MS + 10% coconut milk 2–5 mg liter^{-1} BA, MS + 1 mg liter^{-1} 2,4-D, 0.1 mg liter^{-1} NAA, 1 mg liter^{-1} BA, 0.5 mg liter^{-1} kinetin	Regeneration of plantlets organogenesis and regeneration of plantlets	Rao *et al*. (1982); Lukose *et al*. (1993)

through micropropagation can give five- to sixfold increase in the current average productivity of cardamom (Anon, 1996). Micropropagation technique can be used for the following applications (Bajaj *et al.*, 1988).

i. Increase in the propagation rate of plants
ii. Availability of plants throughout the seasons round the year
iii. Protection against pests and diseases under controlled conditions
iv. Production of uniform clones
v. Production of uniform secondary metabolites

In cardamom, different tissue culture approaches have been made use of such as: (1) callusing, (2) adventitious bud formation, and (3) enhanced axillary branching.

The first report of cardamom tissue culture was that published by Rao *et al.* (1982), who achieved regeneration of plants from callus cultures. Nadgauda *et al.* (1983) achieved a multiplication ratio of 1:3 when sprouted buds were cultured in MS medium supplemented with BAP (0.5 mg liter^{-1}), kinetin (0.5 mg liter^{-1}), IAA (2 mg liter^{-1}), calcium pantothenate (0.1 mg liter^{-1}), biotin (0.1 mg liter^{-1}), and coconut water (5%). The plantlets were successfully rooted and grown in the field. Kumar *et al.* (1985) reported direct shoot formation from inflorescence primordium when cultured using MS medium containing NAA, kinetin, and BAP. They could get the plantlets rooted. Reghunath and Bajaj (1992) have provided a detailed treatment of micropropagation methods in cardamom. Lukose *et al.* (1993) used MS medium containing 20% coconut water, 0.5 mg liter^{-1} NAA, 0.2 mg liter^{-1} IBA, 1.0 mg liter^{-1} of 6-benzyladenine, and 0.2 mg liter^{-1} kinetin. The plantlets are rooted in White's basal medium containing 0.5 mg liter^{-1} NAA and hardened in soil–vermiculture mixture. Other reports include those of Priyadarshan and Zachariah (1986), Vatsya *et al.* (1987), Priyadarshan *et al.* (1988), Reghunath (1989), Reghunath and Gopalakrishnan (1991), Nirmal Babu *et al.* (1997b), and Pradip Kumar *et al.* (1997). Indian biotech companies, such as A.V. Thomas and Co. Ltd. and Indo American Hybrid Seeds, based mainly in South India are involved in commercial multiplication of cardamom.

2. Propagation by Callus Culture

Cardamom micropropagation has been discussed in detail by Reghunath and Bajaj (1992). They have investigated various explants, such as shoot primordium, inflorescence primordium, immature inflorescence segments, and immature capsules and tested serial treatments with 95% alcohol, 2–4% sodium hypochlorite, and 0.05–0.2% mercuric chloride for decontamination of explants. Both MS and SH (Schenk-Hildebrandt) media at half and full strengths were tested, along with auxins such as NAA, IAA, and 2,4-D alone and in combination. The cultures on 0.6% agar were incubated

at light intensity of 1000 Lux and 16-h photoperiod. Maximum callus formation was seen in MS medium supplemented with 4 mg liter^{-1} NAA and 1 mg liter^{-1} BAP. This callus on subculturing in an auxin-free medium having 3 mg liter^{-1} BAP and 0.5 mg liter^{-1} kinetin started caulogenesis, with each culture producing six to nine meristemoids and subsequently culturing in the same mediumproduced shoots within 28 days. Coconut water (15%) enhanced caulogenesis.

3. Propagation through Enhanced Axillary Branching Method

Seventeen media formulations using shoot primordial as explants were tested by Priyadarshan *et al.* (1992). They obtained best results with MS medium fortified with IAA, BAP, kinetin, calcium pantothenate, biotin, and coconut water. Reghunath and Bajaj (1992) have outlined the method of culturing, which uses shoot and inflorescence primordial explants, and the media tested were MS, and SH. The SH medium was to be better than the full or half MS medium since it gave 31% more shoot dry weight. Liquid medium culture under agitation using a gyratory shaker produced 111.5% more axillary branches than those cultured in semisolid medium. The cultures were maintained at 23 ± 2°C, light intensity of 3000 Lux and 16-h photoperiod. The number of axillary branches was maximum in the medium containing 4 mg liter^{-1} of BAP and 0.5 mg liter^{-1} of NAA. Axillary branch production was enhanced by coconut water. Var. Mysore and var. Vazhukka produced more axillary branches than that produced by var. Malabar.

The following culture materials have been proposed by Nirmal Babu *et al.* (1997a) for micropropagation.

Explants: Rhizome bits with vegetative buds
Surface sterilization: Washing in running water followed by washing in detergent solution, followed by washing in 0.1% $HgCl_2$
Incubation: 22 ± 2°C, 14-h photoperiod, 3000 Lux
Medium: a. MS + 1 mg liter^{-1} NAA for rooting
b. MS + 1 mg liter^{-1} BAP, 0.5 mg liter^{-1} NAA for multiplication and rooting in one step
In vitro rooting and hardening

The excised axillary shoots can be rooted in a semisolid medium of half strength MS salt and 0.5% activated charcoal for 1 week, followed by subculturing in one-half MS medium containing 1.5 mg liter^{-1} IBA under a light intensity of 3500 Lux (Reghunath and Bajaj, 1992). Rooted shoots were transferred to MS one-half liquid medium containing only mineral salts and were then shifted to green house for hardening. For planting, vermiculite-fine sand (1:1) mixture was found to be the best which gave 92% establishment (Reghunath and Bajaj, 1992).

h. Callus Culturing and Somaclonal Variations. Callus regeneration protocols are important for generating somaclonal variations for future crop improvement. An efficient system for callus regeneration is essential for production of large number of somaclones and such a system has been reported earlier by Rao *et al.* (1982). This procedure was standardized at IISR (Ravindran *et al.*, 1997). High variability was noticed in the case of morphological characters in somaclones in the culture vessel itself (Ravindran *et al.*, 1997). The most striking morphological variant is a needle leaf variant having small needle-shaped leaves which multiply and root profusely in the same modified MS medium. But, its rate of establishment in the nursery and field is reported to be low (Nirmal Babu, personal communication). Nirmal Babu and his colleagues have standardized cell culture system for large-scale production of callus through somatic embryogenesis to enhance genetic variability. These somaclones are being tested for virus resistance and other characters (Nirmal Babu, unpublished).

Graphic depiction of tissue culture cycle in cardamom (after Ravindran *et al.*, 1997) is shown in Fig. 1.

i. Field testing of Tissue-Cultured Plants. The earliest report on field testing of tissue cultured (TC) plants was that of Lukose *et al.* (1993), although, earlier Nadgauda *et al.* (1983) mentioned about the field establishment of TC plants of cardamom. Lukose *et al.* (1993) carried out two statistically laid out trials to evaluate TC plants together with suckers and seedlings.

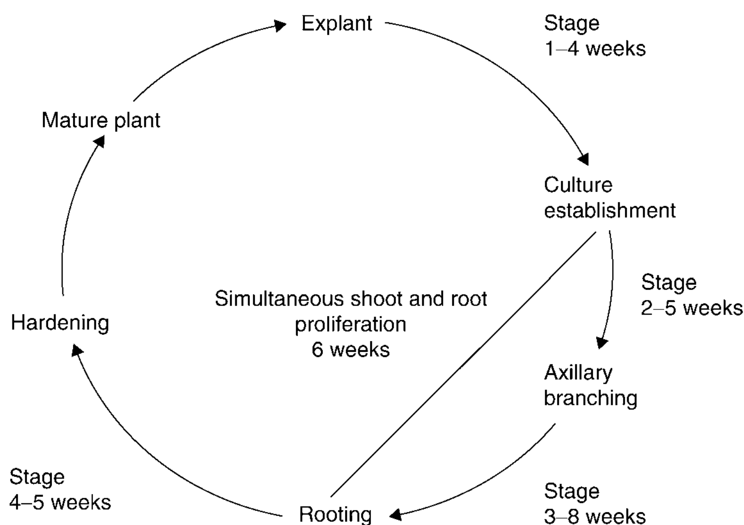


Figure 1 Tissue culture cycle in cardamom (Ravindran *et al.*, 1997).

Trial one was conducted with Clone-37 and the trial two was with the cultivar Mudigere-1. Variations observed among TC plants, suckers, and seedlings were nonsignificant for most of the vegetative characters as shown by analyzing pooled data of 4 years. Yielding tillers, panicles per plant, green capsule yield, and cumulative yield were significantly more in TC plants in both trials. The earlier differences observed in growth characters disappeared during later years. Sudarshan *et al.* (1997) reported the results of a large-scale evaluation carried out by Indian Cardamom Research Institute. In one case, performance of eight high-yielding micropropagated clones and open pollinated progenies were evaluated at 56 locations in an area of 37.5 ha. Unfortunately, suckers were not included in the trial. Variability was observed in the clonal population for vegetative characters. The overall variability in TC plants was 4.5% as against 3% in open pollinated seedling progenies for a given set of characters. Complete sterility was also reported in certain clones. Microcapsules were significantly more in TC plants, accounting for a major share of variation in these plants, which was 8.4%. However, despite variations, TC plants yielded 34% more than open pollinated seedlings. Reasons for variations were adventitious bud formation during micropropagation via axillary buds, genetic instability of adventitious meristem, and tissue culture induced disorganization of meristems (Sudarshan *et al.*, 1997). Chandrappa *et al.* (1997) tested eight TC cardamom selections against their suckers and two local checks. Of the clones, TC 5, TC 6, and TC 7 were found promising, and they differed among themselves inasmuch as yield and other yield attributes were concerned. TC 5 was the best, recording superior values for most observations.

5. *In Vitro* Conservation

In vitro conservation is an alternative method for medium-term conservation. *In vitro* gene bank will be a safe alternative in protecting the genetic resources from epidemic diseases.

Geetha *et al.* (1995) and Nirmal Babu *et al.* (1994, 1999a,b) reported conservation of cardamom germplasm in *in vitro* gene bank by slow growth. The above researchers carried out various trials to achieve an ideal culture condition under which the growth is slowed down to the minimum without affecting the physiology or genetic make up of the plant. The slow growth is achieved by the incorporation of agents for increasing the osmotic potential of the medium such as mannitol. They found that half strength MS without growth regulators and with 10 mg liter^{-1} each of sucrose and mannitol was the best for *in vitro* storage of cardamom under slow growth. By using the above medium in screw-capped vials, the subculture interval could be extended up to 1 year or more, when incubated at 22 ± 2°C at 2500 Lux and at

a photoperiod of 10 h. Low temperature storage at 5 and 10°C was found to be lethal for cardamom, since the cultures did not last more than 3 weeks (Geetha *et al.*, 1995).

Additional research in biotechnology

a. *Isolation and culture of protoplast*: Protoplasts could be isolated from mesophyll tissues collected from *in vitro* grown plantlets, achieving an yield of 35×10^5 g^{-1} of leaf tissue on incubation in an enzyme solution containing 0.5% macerozyme R 10, 2% Onozuka cellulase R 10, and 9% mannitol for 18–20 h at 25°C in dark (Geetha *et al.*, 2000; IISR, 1996). The yield of protoplasts from cell suspension culture was 1.5×10^5 g^{-1} tissue, when incubated in 1% macerozyne R 10 and 2% Onozuka cellulase R 10 for 24 h at 25°C with gentle shaking at 53 rpm in dark. The viability of the protoplast was 75% (mesophyll) and 40% (cell suspension), respectively. The protoplasts on culturing developed into microcalli (Geetha *et al.*, 2000).
b. *Cryoconservation*: Cryoconservation of cardamom seed was first attempted by Chaudhary and Chandel (1995). They tried to conserve seeds at ultralow temperature by either (1) suspending seeds in cryovials in vapor phase of liquid nitrogen (–150°C) by slow freezing or by direct immersion in liquid nitrogen (–196°C) by fast freezing. Results showed seeds to possess 7.7–14.3% moisture content which could be successfully cryopreserved and showed more than 80% germination when tested after 1-year storage in vapor phase of liquid nitrogen at 150°C.
c. *Synthetic seeds*: The first report of synthetic seeds production by encapsulation of shoot tips was by Ganapathy *et al.* (1994). These authors encapsulated shoot tips of cardamom variety Malabar, isolated from multiple shoots and encapsulated in 3% w/w sodium alginate, with different gel matrices, and were subsequently cultured in MS medium. Sajina *et al.* (1997b) reported the standardization of synthetic seeds production in many species including cardamom. Synthetic seeds have many advantages over the normal micropropagation methods. This is an ideal system for conservation and exchange.

6. Conclusions

Despite the fact that cardamom is a native of South India and is being used for the last many centuries, there still exist many gaps in our true understanding of this plant. Botany of cardamom has only been researched so superficially. Developmental morphology and physiology have totally been neglected. Production physiology merits thorough investigation. Information on origin and interrelationships in cardamom, as it is represented by

a single species, is practically nonexistent. Questions, such as how far are Indian species related to Sri Lankan or Malaysian species, are not at all answered. These aspects merit further studies. In the area of crop improvement, emphasis must be given on developing lines resistant to drought, as it is a major yield constraint. Exploitation of heterosis was not attempted, and for this, genetically homozygous lines need to be evolved first. Attempts are on at IISR, Calicut, in developing a protocol for anther culture and production of haploids and dihaploids in cardamom. One of the most pressing areas for research would be breeding for disease resistance, especially against the devastating virus diseases. Biotechnology can contribute much in this area. Yet, another area of considerable importance is molecular characterization of cardamom germplasm. Concerted efforts are required in this area. Alleviation of production constraints through conventional breeding or through molecular approaches will go a long way in enhancing productivity and sustaining it.

III. CARDAMOM CHEMISTRY

There are three forms in which cardamom is used for flavoring, namely, whole, decorticated seeds, and fully ground into powder. Cardamom is distilled for essential oils and solvent extracted for oleoresin. In international trade, generally whole cardamom is the item of commerce. Trade in decorticated form is small, while that in powdered form is practically negligible. The aroma and flavor in cardamom are obtained from the essential oils. As early as 1908, there were reports that cardamom contained terpinene, sabinene, limonene, 1,8-cineole, α-terpineol, α-terpinyl acetate, terpinen-4yl formate, and acetate and terpinen-4-ol (Guenther, 1975). The characteristic odor and flavor of cardamom are determined by the relative composition of the ingredients of the volatile oil (Tables IX and X).

Dried fruit of cardamom contains steam-volatile oil, fixed fatty oil, pigments, proteins, cellulose, pentosans, sugars, starch, silica, calcium oxalate, and minerals. The major constituent of the seed is starch, up to 50%, while the crude fiber is up to 31% in the fruit husk. The constituents of the spice differ among varieties, variations in environmental conditions of growth, harvesting, drying procedures, and subsequent duration as well as conditions of storage. The main factor which determines the quality of cardamom is the content and composition of volatile oil, which determine flavor and aroma. Fruit color does not affect intrinsic organoleptic characteristics. However, faded fruit color generally indicates a product stored for a longer period and possibly deterioration in the organoleptic characteristics through evaporation of the volatile oil (Purseglove *et al.*, 1981).

Table IX
The Principal Components of Cardamom Volatile Oil

Component	Total oil (%)
α-Pinene	1.5
β-Pinene	0.2
Sabinene	2.8
Myrcene	1.6
α-Phellandrene	0.2
Limonene	11.6
1,8-Cineole	36.3
Terpinene	0.7
Cymene	0.1
Terpinolene	0.5
Linalool	3.0
Linalyl acetate	2.5
Terpinen-4-ol	0.9
α-Terpineol	2.6
α-Terpinyl acetate	31.3
Citronellol	0.3
Nerol	0.5
Geraniol	0.5
Methyl eugenol	0.2
Trans-nerolidol	2.7

Table X
Specification of Volatile Oil

Definition, source	Volatile oil distilled from seeds of *Elettaria cadamomum* (Linn.) Maton. Family: Zingiberaceae; cardamom grown in South India, Sri Lanka, Guatemala, Indonesia, Thailand, and South China
Physical and chemical constraints	Appearance: Colorless to very pale-yellow liquid. Odor and taste: aromatic, penetrating, somewhat camphoraceous odor, persistently pungent, strongly aromatic taste. Specific gravity: 0.917–0.947 at 25°C; optical rotation: +22° to +44°; refractive index: 1.463–1.466 at 20°C
Descriptive characteristics	Solubility: 70% alcohol in five volumes, occasional opalescence
	Benzyl alcohol: in all proportions
	Diethyl phthalate: in all proportions
	Fixed oil: in all proportions
	Glycerin: insoluble
	Mineral oil: soluble with opalescence
	Propylene glycol: insoluble
	Stability: unstable in the presence of strong alkali and strong acids; relatively stable to weak organic acids; affected by light
Containers and storage	Glass, aluminum, or suitably lined containers, filled full or tightly closed and stored in cool place, protected from light

Cardamom oil is produced commercially by steam distillation of powdered fruits. The yield and the organoleptic properties of the essential oil so obtained are dependent on many factors. Fruits from recent harvest yield more oil than from the ones stored for a long period. To obtain full recovery of essential oil at least 4-h extraction is essential. Industrial production of cardamom oleoresin is relatively on a smaller scale. Solvent extraction yields about 10% oleoresin and the content depends on the solvent used and the raw material. Cardamom oleoresin contains about 52–58% volatile oil (Purseglove *et al.*, 1981). Oleroresin is used to flavor and is normally dispersed in salt, flour, rusk, or dextrose, before use.

The principal components of cardamom oil are given in Table IX. The volatile oil is extracted from the seeds and the husks hardly give 0.2% oil. Even though the public perception about good quality cardamom is the greenish seed capsule, the appearance of the capsule has but little to do with the recovery of volatile oil (Sarath Kumara *et al.*, 1985). Husk provides good protection and prevents loss of oil from the seeds, and the loss of oil from dehusked seeds is rapid. Seeds start losing oil the moment husk is removed, and this increases with storage time. Bleached cardamom tends to lose oil faster, as the husk becomes very brittle due to bleaching.

Oil from freshly separated seeds or from whole capsules (seeds and husk) is almost identical (Govindarajan *et al.*, 1982a).

Steam distillation is being adopted for oil extraction by most commercial units in India and elsewhere. Cryogrinding using liquid nitrogen is ideal to prevent loss of volatile oil during grinding. Supercritical extraction using liquid carbon dioxide is shown to extract more oil and the flavor is closer to natural cardamom. In oil extraction, the early fractions are rich in low-boiling terpenes and 1,8-cineole and the later fractions are rich in esters. Volatile oil content is highest 20–25 days before full maturity. Ratio of the two main components, 1,8-cineole and α-terpinyl acetate, determine the critical flavor of the oil. The volatile oil from var. Malabar represented by "Coorg Greens" are more "camphory" (smell close to camphor) in aroma, due to the relatively higher content of 1,8-cineole. This oil is reported to be ideal for soft drinks. Early fractions during distillation are dominant in low-boiling monoterpenes and 1,8-cineole. Techniques are available to remove these fractions by fractional distillation so that the remaining oil will have more of α-terpinyl acetate which contributes to the mildly herbaceous, sweet spicy flavor, which is predominant in the var. Mysore or the commercial grade, popularly known as the "Alleppey Green" (Govindarajan *et al.*, 1982b). Eighteen export grades of Indian cardamom, as certified by Agmark (a prominent certification agency in India) were evaluated for their physical and chemical properties (Mathai, 1995). Grades with bigger and heavier capsules "Alleppey Green Extra Bold" (AGEB) and "Coorg Green Extra Bold" (CGEB) were inferior in their flavor constitution compared to the

medium capsule grade ("Alleppey Greeen Small," AGS). Chemical bleaching of the capsules reduced the amount of essential oil in the capsules. Vasanthakumar *et al.* (1989) reported that cardamom at the black seed stage or "karimkai" (the colloquial Malayalam word meaning black seed) is ideal for consumption and essential oil extraction. Gopalakrishnan *et al.* (1989) reported that thrips-infested cardamom capsules contained relatively higher 1,8-cineole. Nirmala Menon *et al.* (1999) extracted bound aroma compounds from fresh green cardamom and the free volatiles were isolated with ether:pentane (1:1) mixture and the bound compounds with methanol. The major compounds in the aglycone fraction were identified as 3-methyl pentan-2-ol, linalool and *cis* and *trans* isomers of nerolidol and farnesol. Noleau and Toulemonde (1987) reported the presence of 122 compounds in cardamom oil cultivated in Costa Rica. These authors have claimed these compounds to be their first discovery.

A. Biosynthesis of Flavor Compounds

1. Sites of Synthesis

Accumulation or secretion of monoterpenes and sesquiterpenes is always associated with the presence of well-defined secretory structures such as oil cells, glandular trichomes, oil or resin ducts, or glandular epidermis. A common feature of these secretory structures is an extra cytoplasmic cavity in which the relatively toxic terpinoid cells and resins appear to be sequestered. This anatomic feature distinguishes the essential oil plants from others in which terpenes are produced as trace constituents that either volatilize inconspicuously or are rapidly metabolized. Several evidences indicate that the secretory structures are also primary sites of mono and sesquiterpene biosynthesis (Francis and O'Connell, 1969).

2. Biological Function

The monoterpenes and sesquiterpenes traditionally have been regarded as functionless metabolic waste products. Yet, certain studies have shown that these compounds can play varied and important roles in mediating the interactions of plants with their environment. The monoterpenes 1,8-cineole and camphor have been shown to inhibit germination and growth of competitors and thus act as allelopathic agents.

3. Early Biosynthetic Steps and Acyclic Precursors

All plants employ the general isoprenoid pathway in the synthesis of certain essential substances. The mono and sesquiterpenes are regarded as diverging at the C10 and C15 stages, respectively in biosynthetic pathways. This, well-known pathway, begins with the condensation of 3-acetyl-CoA in two steps to form hydroxymethyl-glutaryl-CoA which is reduced to mevalonic acid, the precursor of all isoprenoids. A series of phosphorylations and decarboxylation with elimination of the C-3 oxygen function (as phosphate) yields isopentenyl pyrophosphate (IPP) (McCaskill and Croteau, 1995). This is isomerized to dimethylallyl pyrophosphate (DMAPP). This in turn, leads to the synthesis of geranyl pyrophosphate (GPP) and farnesyl pyrophosphate (FPP).

A number of monoterpene cyclases have been investigated in detail especially that which is responsible for the synthesis of α-terpinene, γ-terpinene, and 1,8-cineole. Other cyclizations of interest are cyclization of geranyl pyrophosphate to limonene and cyclization of geranyl pyrophosphate to sabinene, the precursor of C3 oxygenated thujene-type monoterpenes. The biosynthesis of thujene monoterpenes (such as 3-thujene) involves photooxidation of sabinene and also involves α-terpineol and terpinen-4-ol as intermediates (Croteau and Sood, 1985).

The pathways of cyclization of geranyl phosphate and farnesyl pyrophosphate to the corresponding monoterpenes and sesquiterpenes are not similar. The limited information available suggests that monoterpene and sesquiterpene cyclases are incapable of synthesizing larger and smaller analogs. Pinene biosynthesis has been extensively studied. Three monoterpene synthases (cyclases) catalyze the conversion of GPP. Pinene cyclase I converts FPP into bicyclic (+)-α-pinene, (+)-β-pinene, and monocyclic, and acyclic olefins (Bramley, 1997). The biosysnthesis of monoterpenes, limonene, and carvone, proceeds from geranyl diphosphate. Geranyl diphosphate is cyclized to (+)-limonene by monoterpene synthase. This intermediate is either stored in the essential oil ducts without further metabolism or is converted by limonene-6-hydroxylase to (+)-*trans* carveol. This is oxidized by a dehydrogenase to (+)-carveone (Brouwmeester *et al.*, 1998). Turner *et al.* (1999) demonstrated the localization of limonene synthase. Studies in peppermint (Gershenzon *et al.*, 2000) suggested that monoterpene biosynthesis is regulated by genes, enzymes, and cell differentiation.

The biosynthesis of 1,8-cineole is suggested from linalyl pyrophosphate (Clark *et al.*, 2000). Eucalyptol, which is also known as 1,8-cineole is a biosynthetic dead end in many systems, which allows accumulation of large quantities of this compound in many plants. Other than cardamom oil, 1,8-cineole is also found in essential oils of artemisia, basil, betel leaves, black pepper, carrot leaf, cinnamon bark, and also eucalyptus and in many other essential oil-yielding plants. Most of the processes of the terpenoid biosynthesis are associated with cell organelles. Calcium and magnesium play important roles in the biosysthesis

of sesquiterpenes (Preisig and Moreau, 1994). McCaskill and Croteau (1995) indicate that cytoplasmic mevalonic acid pathway is blocked at HMG-CoA reductase and that the IPP utilized for both monoterpene and sesquiterpene biosynthesis are synthesized exclusively in the plastids.

B. Industrial Production

Industrially, cardamom oil is extracted by steam distillation. The distillation unit consists of a material-holding cage, condenser and receiver for steam distillation and adopt conditions for obtaining acceptable quality oil. Usually lower grade capsules harvested after full maturity is used for steam distillation. Such capsules are first dehusked by shearing in a disk mill with wide distances between disks and seeds are separated by vibrating sieves. The dehusked seeds are further crushed to a coarse powder (Govindarajan *et al.*, 1982c). The essential oil containing cells in cardamom seeds are located in a single layer below the epidermis and fine milling will result in volatile oil loss. Cryogrinding using liquid nitrogen is ideal to prevent volatile oil loss. Study on steam distillation revealed that nearly 100% of the volatile oil was recovered in about 1-h time. The composition of the fractions collected at 15 min show that most are hydrocarbons and 1,8-cineole distilled over, while 25–35% of the important aroma contributing esters were also recovered in this time period. Further distillation for 2 h was required to recover remaining esters. Hence, distillation duration of 2–3 h was essential to completely extract the volatile oils.

The value of cardamom as a food and beverage additive depends much on the aroma components which can be recovered as volatile oil. The volatile oil has a spicy odor similar to eucalyptus oil. Oil yield ranges from 3 to 8%, and it varies with varieties, maturity at harvest, commercial grade, freshness of the sample, green or bleached, and distillation efficiency.

1. History

Composition: Nigam *et al.* (1965) reported the detailed analysis of cardamom for the first time. The constituents were identified with the help of gas chromatography and infrared spectroscopy, using authentic reference compounds and published data. Ikeda *et al.* (1962) reported 23.3% of the oil as hydrocarbons with limonene as a major component. They have also reported the presence of methyl heptenone, linalool, linalyl acetate, β-terpineol, geraniol, nerol, neryl acetate, and nerolidol. Compounds present in commercial samples were identified and compared with that of the wild Sri Lankan cardamom oil (Richard *et al.*, 1971). Govindarajan *et al.* (1982c) have elaborated the range of concentration of major flavor constituents, their flavor description, and effect on flavor use. Thin layer chromatography, column chromatography, and subsequently gas chromatography were employed to separate oil constituents. Fractional distillation,

infrared spectroscopy, mass spectrum, and nuclear magnetic resonance (NMR) were adopted to identify the specific compounds. The major constituents identified were α-pinene, α-thujene, β-pinene, myrcene, α-terpinene, γ-terpinene, and penta-cymene. These were identified in the monoterpene hydrocarbon fraction of cardamom oil. Different commercial cardamom samples were compared for their chemical constituents in 1966 and 1967 (Lawrence *et al.*, 1978). Sayed *et al.* (1979) evaluated the oil percentage in different varieties of cardamom. Varieties Mysore and Vazhukka contained the maximum (8%). Percentage by weight of cardamom seeds in the capsules ranged from 68 to 75. Percentage of cardamom seeds is positively correlated to volatile oil (“*r*” = 0.436) on dry seed basis, whereas percentage of husk to volatile oil is negatively correlated (“*r*” = –0.436).

Detailed investigations on the volatile oil revealed large differences in the 1,8-cineole content, as high as 41% in the oil of variety Malabar and as low as 26.5% in the oil of variety Mysore. While the α-terpinyl contents were comparable, the linalool and linyl acetate were markedly higher in variety Mysore. The combination of lower 1,8-cineole with its harsh camphory note and higher linalyl acetate with its sweet, fruity floral odor result in the relatively pleasant mellow flavor in the variety Mysore, represented by the largest selling Indian cardamom grade, namely, Alleppey Green. Zachariah and Lukose (1992) and Zachariah *et al.* (1998) identified cardamom lines with relatively low cineole and high α-terpinyl acetate. An interesting observation is that lines Alleppey Green 221 and 223 gave consistently higher oil yield (7.8%) and high α-terpinyl acetate content (55%). The performance of Alleppey Green 221 was consistent for about five seasons (Zachariah *et al.*, 1998).

Previous gas chromatograms showed up to 31–33% peaks, and up to 23 compounds were identified, while the improved procedure gave higher resolution with more than 150 peaks. All peaks have not been identified. All results, however, confirm the earlier observations that 1,8-cineole and α-terpinyl acetate are the major components in cardamom oil. Many investigators used techniques, which were a combination of fractional distillation, column and gas chromatography, mass spectrometry, infrared spectroscopy, and nuclear magnetic resonance to identify the constituents in cardamom oil. Nirmala Menon *et al.* (1999) have investigated the volatiles of freshly harvested cardamom seeds by adsorption on Amberlite XAD-2, from which the free volatiles were isolated by elution with pentane–ether mixture and glycosidically bound volatiles with methanol. Gas chromatographic–mass spectrometric analysis of the two fractions led to the identification of about 100 compounds. Among the free volatiles the important ones are 1,8-cineole and α-terpinyl acetate. The less important ones are geraniol, α-terpineol, *p*-menth-8-en-2-ol, γ-terpinene, β-pinene, carvone oxide, and so on, while a large number of compounds were present in trace amounts. Among the aglycones, the important ones are 3-methylpentan-2-ol, α-terpineol, isosafrole, β-nerolidol, *trans*, *trans*-farnesol, *trans*, *cis*-farnesol, *cis*, *trans*-farnesol, T-murrolol, cubenol, 10-epi-cubenol, *cis*-linalol-oxide,

tetrahydrolinalol, and so on. Sixty-eight compounds were identified in the volatile fraction while 61 compounds were identified in the glycosidically bound fraction.

2. Evaluation of Flavor Quality

The flavor quality of a specific food item results from the interaction of the chemical constituents contained in the food item with the taste perception of the person enjoying the food item in question. As the second most important spice in the world, next only to black pepper, the most important component of cardamom is the volatile oil with its characteristic aroma, described as sweet, aromatic, spicy, camphory, and so on. Cardamom oil is richer in oxygenated compounds, all of which are potential aroma compounds. Capillary column chromatography and gas chromatography have shown the existence of 150 compounds in cardamom oil. While most of the identified compounds, which are, alcohols, esters, and aldehydes, are commonly found in many spice oils, the dominance of the ether 1,8-cineole and the esters α-terpinyl and linalyl acetates in the composition, renders the volatile oil contained in cardamom a unique one (Raghavan *et al.*, 1991). The bitterness compound present in cardamom is α-terpinyl, present to the extent of about 0.8–2.7%. Govindarajan *et al.* (1982c) had described the esters: 1,8-cineole ratio (Table XI). In rare samples, defective notes

Table XI
Esters and Alcohol Ratios to 1,8-cineole in Cardamom Volatile Oils

Source	Ratio		
	α-Terpinyl acetate	α-Terpinyl + linalyl acetate	Esters + linalool + α-terpineol
Alleppey Green (var. Mysore)	1.30	1.59	1.77
Alleppey Green (var. Mysore)	1.10	1.19	1.43
Kerala, Ceylon (var. Mysore)	0.83	0.91	1.03
Ceylon, commercial	1.21–1.77	–	–
Ceylon, from extract	1.67–2.40	–	–
Ceylon, green expressed (var. Mysore)	1.69	1.80	1.91
Ceylon, green from extract	2.40	2.64	2.83
Ceylon, green expressed (var. Mysore)	2.17	2.40	2.68
Coorg green (var. Malabar)	0.73	0.77	0.80

Source: Govindarajan *et al.* (1982).

Table XII
Flavor Profile of Cardamom Oil and Extracts

Desirable notes	Defective notes
Fresh cooling	Unbalanced
CAMPHORACEOUS	Sharp/Harsh
Green	Heavy
SWEET SPICY	Earthy
FLORAL	Oily (Vegetable) oxidized
WOODY/BALSAMIC	Resinous
Herbal	Oxidized terpinic
Citrus	
Minty	
Husky	
Astringent, weakly	Bitter

Source: Govindarajan *et al.* (1982).
Note: The descriptions in capital letters are the perceived dominant characteristics, the defectives are arranged in the order of increasing impact on flavor.

Table XIII
Volatile Oil Profile of Cardamom

Origin	Commercially distilled from Alleppey Green varieties
Odor	**Initial impact** Penetrating, slightly irritating Cineolic, cooling Camphoraceous, disinfectant like warm, spicy Sweet, very aromatic, pleasing Fruity, lemony, citrus-like
	Persistance The oil rapidly "airs off" on a smelling, strip losing its freshness, becomes herby, woody, with a marked musty "back-note"
	Dry out No residual odor after 24 h

Source: Heath (1978).

described as slightly "oxidized terpinic" were noted at high-dilution levels but were overshadowed by total cardamom aroma at higher level of concentrations. Markedly camphory samples (lacking sweet aromatic components) or high in defectives, oxidized terpinic, resinous, oily, earthy or bitter in flavor, are rated poor and unacceptable. The authors suggested that quality grading of cardamom is possible by observing three major attributes of balance of profile, intensity/tenacity and absence of defects. The desirable and defective notes of cardamom oil are described in Table XII. The general profile of the popular Alleppey Green is described in Table XIII.

Analysis of a Japanese cardamom oil sample indicated the presence of some new compounds like 1,4-cineole, *cis-p*-menth-2-en-1-ol, and *trans-p*-menth-2-en-1-ol, all of them in extremely low amounts of 0.1–0.2%. Cardamom oil from Sri Lanka gave a high range of values for α-pinene plus sabinene 4.5–8.7% and linalool 3.6–6% and a wider range for the principal components 1,8-cineole 27–36.1% and α-terpinyl acetate 38.5–47.9% (Govindarajan *et al.*, 1982). Some compounds, such as α-thujene, sabinene, *p*-cymene, 2-undecanone, 2-tri-decanone, heptacosane or *cis* and *trans-p*-menth-2-en-1-ols, were rarely detected in cardamom samples. Components, such as camphor, borneol, and citrals, might modify the overall flavor quality of cardamom, mainly determined by a combination of terpinyl and linyl acetate and cineole. Locations where the crop is grown also affect in altering the concentration of linalool, limonene, α-terpineol, and so on. The quality of flavor depends on interaction of chemical constituents of food with human taste buds and the perception of taste by individuals depends on different attributes. A casual relationship of physical and chemical characteristics of food and their sensory perception and judgment by human assessors has to be made to establish a meaningful judgment of quality. According to many investigators, the ratio of 1,8-cineole to α-terpinyl acetate is a fairly good index of the purity and authenticity of cardamom volatile oil (Purseglove *et al.*, 1981). The ratio is around 0.7–1.4. Cardamom Research Center at Appangala, Coorg district in the State of Karnataka, India under the administrative control of the Indian Institute of Spices Research, at Calicut, Kerala State, India, under the overall administrative control of the Indian Council of Agricultural Research at New Delhi, India, could collect many accessions from cardamom-growing areas with flavor ratio of more than one. Both 1,8-cineole and α-terpinyl acetate together with terpene alcohols (linalool, terpinen-4-ol, and α-terpineol are important for the evaluation of aroma quality. The oils from variety Malabar exhibit the lowest flavor ratio while that from variety Mysore has high flavor ratio. Cardamom samples from Sri Lanka and Guatemala have higher ratios indicating their superiority in flavor, similar to that of variety Mysore. The occurrence of components, such as borneol and citral, modifies the flavor quality. Pillai *et al.* (1984) made a comparative study of the 1,8-cineole and α-terpinyl acetate contents of cardamom oils derived from diverse sources (Table XIV). Their investigation indicated that Guatemalan cardamom oil is marginally superior to Indian cardamom oil due to the higher content of α-terpinyl acetate content. The high concentration of 1,8-cineole makes the oil from PNG poor. The above-mentioned investigators found fair degree of concordance in the infrared spectra (IR) of oils irrespective of their origin. The IR spectra provide a fingerprint of the oil as it projects the functional groups and partial structures that are present. The spctrum also helps in tracking the aging process of the oil.

Table XIV
Percentage of 1,8-Cineole and Terpinyl Acetate in Volatile Oils of Cardamom Grown in Different Regions

	Percentage of oil	
Origin	1,8-Cineole	α-Terpinyl acetate
Guatemala I	36.40	31.80
Guatemala II	38.00	38.40
Guatemalayan Malabar Type	23.40	50.70
Guatemalayan I	39.08	40.26
Guatemalayan II	35.36	41.03
Synthite (commercial grade)	46.91	36.79
Mysore-type (Ceylon)	44.00	37.00
Malabar-type (Ceylon)	31.00	52.50
Mysore I	49.50	30.60
Mysore II	41.70	45.90
Mysore	41.00	30.00
Malabar I	28.00	45.50
Malabar II	43.50	45.10
Ceylon type	36.00	30.00
Alleppey I	38.80	33.30
Alleppey Green	26.50	34.50
Coorg Green	41.00	30.00
Mangalore I	56.10	23.20
Mangalore II	51.20	35.60
Papua New Guinea (PNG)	63.03	29.09
Cardamom oil (Indian origin)	36.30	31.30

Source: Pillai *et al*. (1984).

The extraction methods like cryogenic grinding (Gopalakrishnan *et al*., 1991) and supercritical extraction also influence the flavor profile. Such extraction techniques can extract the trace compounds which are otherwise lost in other methods of extraction.

3. Cardamom Oleoresins and Extract

Total solvent extract or oleoresin is known to reflect the flavor quality more closely than the distilled volatile oil. In the case of cardamom, oil, more or less, represents both flavor and taste. The stability of oleoresin depends on the changes which occur to the fat and terpenic compounds which are usually susceptible to oxidative changes. Existing investigations point to the fact that there exists a distinct difference in the flavor profile among cardamom varieties, which in turn is influenced by agroclimatic conditions, postharvest processing, and cultural practices.

4. Variability in Composition

Analysis of germplasm collections, which have been conserved at the Indian Institute of Spices Regional Rsearch Station at Appangala, Coorg district, Karnataka State, India, under the administrative control of the Indian Council of Agricultural Research in New Delhi, indicated distinct variability in oil content and concentration of the two important components of the oil, α-terpinyl acetate and 1,8-cineole. Selective breeding of the high quality accessions which have low 1,8-cineole content and high α-terpinyl acetate content, such as Appangala 221 (AG 221), will go a long way in enhancing the total flavor quality of Indian cardamom varieties.

5. Pharmaceutical Properties of Cardamom Oil

Cardamom oil possesses both antibacterial and antifungal properties. The chemical composition, physicochemical properties, and antimicrobial activity of dried cardamom fruits to assess potential usefulness of cardamom oil as a preservative has been investigated by Badei *et al.* (1991a,b). The antimicrobial effect of the cardamom oil was tested against nine bacterial strains, one fungus, and one yeast, which showed that the oil was as effective as 28.9% phenol. Minimal inhibitory concentration of the oil was 0.7 mg ml^{-1}, and it was concluded that cardamom oil could be used at a minimal inhibitory concentration range of 0.5–0.9 mg ml^{-1} with any adverse effect, whatsoever, on flavor quality. Cardamom oil is effective as an antioxidant for cottonseed oil, as assessed by stability, peroxide number, refractive index, specific gravity, and rancid odor. The effect is enhanced by increasing cardamom oil content in cottonseed from 100 to 5000 ppm. Organoleptic evaluation showed that addition of up to 1000 ppm cardamom oil did not adversely affect the specific odor of cottonseed oil.

6. Fixed Oil of Cardamom Seeds

In addition to volatile oil, cardamom seeds also contain fixed fatty oil. Composition of fatty oil has been investigated and found to contain mainly oleic and palmitic acids (Table XV). Gopalakrishnan *et al.* (1990), who carried out investigations based on nuclear magnetic resonance and mass spectroscopy reported that nonsaponifiable lipid fraction of cardamom consisted mainly of waxes and sterols. Waxes identified were, *n*-alkanes (C21, C23, C25, C27, C29, C31, and C33). In the sterol fraction, β-sitosterol, and γ-sitosterol were reported. Phytol and traces of eugenyl acetate were also identified in cardamom.

Table XV
The Fixed Fatty Oil Composition of Cardamom Seed

Fixed fatty acid	Total fixed oil (%)
Oleic	42.5–44.2
Palmitic	28.4–38.0
Linoleic	2.2–15.3
Linolenic	5.8
Caproic	5.3
Stearic	3.2
Hexadecanoic	1.9
Caprylic	5.3
Capric	<0.1–3.8
Myristic	1.3–1.4
Arachidic	0.2–2.1
Hexadecanoic	1.9
Pentadecanoic	0.4
Lauric	0.2

Source: Verghese (1996).

7. Conclusions

The cardamom plant is a wonderful gift of nature and from a biochemical point of view, its volatile oil is so delicately constructed by kaleidoscopic permutations and combinations of terpenes, terpene alcohols, esters, and other compounds, which defy even precise and sophisticated analytical techniques. As of now, concocting "synthetic cardamom oil" from its components found in nature having identical sensory qualities is well beyond human capabilities. It needs to be said so here because in the case of black pepper, such an attempt has been made. The sensory analysis, regarded by food scientists as the touchstone of quality, is very sensitive to concentrations ranging from 10–8 ppm to 10–4 ppm. The superiority of the variety Alleppey Green is attributed to its superior sensory qualities. In totality, it has a much better perception of flavor, which need not necessarily be dependent on the relative concentration of any component. However, the natural quality is often lost during the extraction process, storage, and postharvest handling. The flavor quality can be enhanced by cryogrinding and super critical fluid extraction. Indexing genetic resources for flavor quality and incorporation into breeding program, the superior quality genotypes can go a long way in improving the overall flavor quality of cardamom. Chemical finger printing of the cardamom genotypes available in the germplasm conservatories using infrared, gas chromatography, mass spectroscopy, or nuclear magnetic resonance spectral characters, as well as by sensory evaluation, is needed to pick up the really superior genotypes for flavor quality.

IV. THE AGRONOMY OF CARDAMOM

A. Distribution

Cardamom cultivation is mostly concentrated in the evergreen forests of the Western Ghats in South India. Besides India, the crop is grown commercially in Guatemala, on a small scale in Tanzania, Sri Lanka, El Salvador, Vietnam, Laos, Cambodia, and PNG. Earlier, India accounted for 70% of the world production, which has now slid to 41%, while Guatemala contributes around 48%. Total area of cardamom in India was 1,05,000 ha until the 1980s, which has now come down to about 75,000 ha. It is principally cultivated in three southern states in India, namely, Kerala, Karnataka, and Tamil Nadu, which contribute approximately 60%, 31%, and 9%, respectively. Cardamom is cultivated mostly under natural forest canopy, except in certain areas in Karnataka (North Karnataka, Chickmagalur, and Hassan districts) and Wayanad district in Kerala State, where it is often grown as a subsidiary crop in arecanut and coffee gardens. The important areas of cultivation in India are Uttar Kannada, Shimoga, Hassan, Chickmagalur, and Kodagu (Coorg) in Karnataka State, northern and southern foot hills of Nilgiri district in Tamil Nadu, parts of Madurai, Salem, Tirunelveli, Annamalai, and Coimbatore districts, also in Tamil Nadu. Wayanad and Idukki districts in Kerala State as well as Nelliapathy hills of Palakkad districts are also home to cardamom.

B. Climate

Altitude: The optimum altitudinal range for cardamom is between 600 and 1500 m amsl (Anon, 1976, 1982). In South India, all cardamom plantations lie between 700 and 1300 m amsl, and go rarely up to 1500 m amsl, where growth is poor. Cardamom cultivation is restricted to the Western Ghats which constitute an extensive chain of hills parallel to the West Coast of peninsular India. Variety Malabar, traditionally grown in Karnataka, can also grow at lower elevations of 500–700 m (Abraham and Tulasidas, 1958). At lower elevation, vegetative growth is satisfactory, fruit production is poor. In Guatemala, cardamom is grown at varying altitudes, ranging from 900 to 1200 m amsl. Most of the plantations in the southern India are at high altitudes, while in northern India the crop grows both at low and high elevations (George, 1990). Cardamom is highly sensitive to elevation and the wrong choice of cultivar, or inappropriate location, in terms of elevation, can severely affect growth and productivity. The crop is also

highly prone to wind and drought damage, and therefore, areas liable to be affected by such conditions are unsuitable (Mohanchandran, 1984).

1. Temperature

Guatemalan climate offers the ideal conditions for good cardamom growth and productivity. Annual average temperature varies from 17 to 25°C in the southern part and 18–23.5°C in the northern part (George, 1990). In India, optimum growth and development are observed in the warm and humid conditions at a temperature range of 10–35°C (Anon, 1976). The upper temperature limit will normally be around 31–35°C. In the eastern side of the Western Ghats, a combination of desiccating winds passing from the hinter lands of east and low humidity leads to desiccation and drying of plants. In such areas protective irrigation would be essential for retention of humid conditions for adequate growth, panicle initiation, and capsule setting (Korikanthimath, 1991). It is noticed that the spread of the dreaded "Katte" disease is more during summer than in the monsoon season. Cold conditions result in almost poor or no capsule setting. Hence, for healthy growth of cardamom plants, extremes of temperature or diurnal wind are not conducive.

2. Rainfall

In South India cardamom is grown under a range of rainfall from 1500 to 5750 mm annually. Climate of the area is determined by the annual rainfall and the year can be divided, generally, into winter, summer, and monsoon seasons. Cool temperature and relatively dry weather prevails from November to February. Hot weather prevails from March to June, marked by moderate to high temperature and occasional showers. Southwest monsoon sets in June and continues until early September. In the more westerly areas of the hills, rains during this period are heavy and continuous, but they decrease considerably in the eastern slopes, which experience strong winds, much cloud, and frequent light showers. After a short gap, the northeast rains commence and occasional rains continue up to December. This is a dry period in the more northerly and westerly areas, but is marked by heavy rains and overcast skies in the south and the east (Mayne, 1951b,c). In general, cardamom-growing areas of Karnataka State and many regions of the Idukki and Wayanad districts of Kerala State experience a dry period extending from November–December to May–June. Such a long dry period of 6–7 months is, in fact, the principal constraint to good cardamom production.

The Indian average cardamom yield is only 149 kg ha^{-1} compared to the Guatemalan and Papua New Gunea yield of 300 kg ha^{-1}. Well-distributed

rainfall contributes to good yield in Guatemala (Mohanchandran, 1984). In India, 70–80% of the total cardamom area is rainfed (Charles, 1986). Following forest denudation in many parts of Western Ghats, normal congenial habitat for cardamom has been adversely affected, destabilizing the ideal cool humid microclimate and the productivity of the crop.

Investigations on the effect of rainfall on cardamom productivity indicate that contribution of rainfall distribution is more important than total rainfall received and the number of rainy days. Data collected from cardamom plantations indicate that of the 10 from 13 investigated, highest yield was from those plantations receiving less than 2000-mm annual rainfall. In another survey, data from 57 locations in the Coorg district of Karnataka State indicate that in 42 cases more than 100 kg ha^{-1} dry capsule yield was obtained when the annual rainfall was less than 2000 mm. This clearly indicates that total rainfall is not the major determinant in cardamom productivity, and even 2000 mm of rainfall well-distributed might suffice (Ratnam and Korikanthimath, 1985; Subbarao and Korikanthimath, 1983). Most of the rainfall received during June–August would result in runoff leading to severe soil erosion, and hence, proper soil conservation measures are required to minimize soil and land degradation. Storing of run off water during rainy periods in suitable farm ponds, tanks, or embankments and recycling it during summer as protective irrigation coinciding with critical physiological stages of the crop offer great scope for evading total crop failure and stability of yield (Cherian, 1977; Korikanthimath, 1987a).

In Guatemala, rainfall conditions are a lot more favorable than in India. It varies from 2000 to 5000 mm in cardamom-growing areas and the rainfall is evenly distributed throughout the year. Two peaks do occur. As there are no heat and drought stresses, as in India, cardamom yields in Guatemala are much higher than that obtained in India, and on average stands at 300 kg ha^{-1}. Similar situation occurs in PNG as well, leading to high yields (Krishna, 1968, 1997). In India, a prolonged drought in the first 6 months of the year had a devastating effect which led to significant crop loss especially in exposed and partially shaded regions of Idukki district of Kerala State. India's cardamom production came down to the lowest level of 1600 million tonnes, which showed an imminent need to combat recurring drought by proper soil moisture conservation techniques, mulching, adequate shade management along with provision for life-saving irrigation.

C. Management Aspects

1. Planting Systems

Following are the four principal planting systems (Mayne, 1951a).

a. Kodagu (Coorg district in Karnataka State) Malay system

b. North Kanara (North Kanara district of Karnataka State) system
c. Southern system
d. Mysore (Karnataka State) system.

2. Kodagu Malay System

It is restricted to Coorg district in Karnataka State. Small patches of forest land, a quarter-one-sixth hectare in area, are cleared and planted with cardamom. Care is taken in selecting plots which face north or northeast to ensure adequate lateral shade from surrounding forest trees. Seedlings from natural regeneration are thinned out and spaces filled in, or seedlings are raised in nurseries and transplanted in shallow pits, 1.5–2.5 m apart. The areas are weeded periodically either using chemical weedicides or manually. The most commonly grown variety is Malabar. After about 15 years the area is left to natural forest cover, while the cardamom cultivation is shifted to another patch of land. A somewhat similar system was followed by the Madras (now Chennai in Tamil Nadu) Forest Department earlier and cardamom was collected as a minor forest produce, the areas partially cleared by selection felling.

3. North Kanara System

This system is followed in the districts of North Kanara, Shimoga, and parts of Chickmagalur in the State of Karnataka where cardamom is grown as a secondary crop in arecanut gardens. Seedlings are raised in nurseries and planted in rows, 1.5–1.8 m apart. About 1200 seedlings are planted per hectare. Malabar is the variety usually grown. Cardamom is planted on the margins of arecanut gardens (*Areca catechu*, beetel nut—a common nut used for chewing in India and Pakistan).

4. Southern System

This is the system most in vogue for commercial cultivation of cardamom and accounts for about 90% of the cardamom plantations in India. Selected areas are cleared of jungle land and all undergrowth, thinning out the overhead shade, planting cardamom seedlings at regular distance, and cultivating according to a regular schedule. This system is adopted in the States of Kerala, Karnataka, and Tamil Nadu. The sizes of the holdings vary widely, but greater part of the production comes from holdings of 2–20 ha. In most areas of Nilgiris district in Tamil Nadu, Kerala State and Tamil

Nadu, the principal types of cardamom grown are varieties Mysore and Vazhukka. In Karnataka State, Malabar is the exclusive variety grown.

5. Mysore System

Coffee is the most popular plantation crop of Karnataka State where cardamom is grown in isolated pockets, in ravines or in low-lying areas of coffee plantations. In such situations, cardamom is found either as a sole crop in narrow strips along the ravines or as scattered clumps interspersed with coffee plants.

D. Establishing a Cardamom Plantation

1. Preparation of the Main Field

Where cardamom is cultivated on a plantation scale in virgin forest, the first step consists of clearing all undergrowth and thinning out overhead canopy in order to obtain an even density of shade. If the land is slopy, it would be preferable to start clearing from top and work downwards. The shade will have to be regulated in such a way so as to allow sunlight to filter through tree canopy almost uniformly. The bushes, shrubs, and undergrowth are cut and heaped in rows or in piles and allowed to decay. In the case of steep slopes, it would be preferable to utilize such debris in a manner to assist checking any soil movement due to erosion. Contour terraces may be formed in cases where the land is too steep. In arecanut gardens, deep trenches, and pits are dug among palms and filled up with fresh soil brought from neighboring forest. The ground so prepared is utilized for planting. In marshy areas, adequate provisions should be made to drain off excess water by providing main and lateral drains depending on natural gradient of the land where the plantation is being established.

2. Spacing

Variety grown and duration of the crop determine spacing. Where it is intended to grow on a regular replanting manner and for a limited cycle, it is obviously desirable to plant as closely as possible, without unduly restricting the plants, so that early crops may be as large as possible. If a crop is meant to last 10 years, with a commonly suggested crop cycle, only eight harvests are likely to be taken and the first two at least will be dependent on the number of plants per hectare. If, on the other hand, plantings are expected to remain in

the field for longer periods, too close planting will lead to overcrowding and yield reduction. This is important since cardamom clumps tend to spread outwards as they age and gradually new shoot production will decline in the center of the plant. It will also lead to yield reduction as the crop ages. Korikanthimath (1983b) investigated the effect of spacing, seedling age, and their performance in relation to fertilizer rates and found that tiller number, number of leaves per plant, and plant height were significantly affected by the different treatments. Maximum tiller number (10.9 per plant) and maximum number of leaves (102.1 per plant) were seen in the case of 18-month-old seedlings planted at 2 m × 1 m spacing and the plants were fertilized with N, P, and K in the ratio of 75:75:150 kg ha^{-1} and a supplemental 100 kg ha^{-1} neem (*Azadirachta indica*) cake. In another similar investigation, where spacing and fertilizer rates were considered, under rainfed conditions, the treatment differences turned out to be highly significant inasmuch as tiller number and leaf number per plant were concerned. A spacing of 2 m × 1.5 m combined with a fertilizer schedule of 75:75:150 kg N, P, and K per hectare resulted in maximum tiller number and leaves per plant (Korikanthimath, 1982). Normal spacing adopted in the case of the vigorous variety Mysore is 3 m × 3 m, and for the less vigorous variety Malabar 2 m × 2 m spacing is adopted (Anon, 1976). In the "high-production technology" field demonstration plots, primarily meant to show the farmers, spacing at 2 m × 1 m on hill slopes along the contour and spacing at 2 m × 1.2 m on flat lands, gentle slopes, and valley bottoms, yielded 500 kg dry capsules ha^{-1} within 2 years from the date of planting (Korikanthimath and Venugopal, 1989). In a spacing trial carried out at Yercaud, in Tamil Nadu, it was observed that close spacing at 1 m × 1 m and 1.5 m × 1.5 m resulted in better yield per unit area than in the case of wider spacing at 2.5 m × 2.5 m and 2 m × 2 m. In slopy lands, it is advisable to make contour terraces in advance of the planting date and pits may be dug along the contour for planting. Depending on the slope, a distance of 4–6 m may be provided along the slope between the contour lines. Close planting may be adopted along the contour.

3. Methods of Planting

The factors which determine the planting systems are the land, soil fertility, and the probable period over which the plantation is expected to last. Seedlings are planted in holes in some places, which are scooped out at the time of planting. In other areas, considerable care is taken in preparing pits for planting. Spots where pits are to be dug are marked with stakes, soil dug out from the pits, and they are filled with surface soil mixed with leaf mould, compost, or cattle manure (Subbaiah, 1940). Commonly pit size is 60 cm × 60 cm × 45 cm. Some plantations use pit size of 90 cm × 90 cm ×

90 cm or 120 cm × 120 cm × 30 cm. In South and North Kanara in the State of Karnataka, pits are of smaller size, namely, 45 cm × 45 cm × 45 cm (Mayne, 1951a). In the State of Kerala, varieties Mysore and Vazhukka are planted in pit size of 60 cm × of 45 cm × 45 cm. Normally pits are opened during the months of April–May, after the premonsoon showers. Pits are filled with a mixture of top soil and compost or well-rotten farm yard manure and 100 g of rock phosphate. In slopy land, contour terraces are made sufficiently in advance of planting and the pits are dug along the contour (Anon, 1985, 1986). Most of the cardamom-growing tracts are situated on hill slopes of Western Ghats. The undulating terrain and heavy rainfall in the region increase the problem of soil erosion and loss of plant nutrients in run off. This implies the need to conserve enough moisture, while at the same time, ensure safe disposal of excess rainfall. In view of these pressing demands, investigations under rainfed conditions on planting-fertilizer treatments were carried out at Cardamom Research Center at Appangala, Karnataka State, under the administrative control of the Indian Council of Agriculture Research. These investigations were started in 1985. Some of the results are included in Table XVI. Korikanthimath (1989) reported greater moisture retention under the trench system of planting than in the case of pit system of planting and concluded the former to be better than the latter.

Trenches may be dug to a depth of 30 cm × 45 cm wide up to any length across the slope or along the contour. Top 15 cm soil may be removed and kept separately, while the lower 15 cm soil excavated from trenches placed below the one above. The top 15 cm soil is filled back into the trench with cattle manure. While closing the trench, about 5 cm space may be left at the top to facilitate application of fertilizers and mulches. Although digging trenches would be about 30–40% more expensive than digging pits, it may be worth attempting because of the benefits of soil moisture conservation and its ultimate beneficial effect on plant growth and yield. However, in low-lying areas, where the danger of water stagnation is real, pit system may be preferable.

Table XVI
Dry Cardamom Yield (kg/ha) Influenced by Planting System and Fertilizer Rates

	NPK fertilizer (kg ha^{-1}) (B)					
Planting system (A)	0:0:0	40:80:160	80:80:160	120:120:240	160:160:320	Mean
Pit	123.9	277.5	388.9	437.0	455.6	336.0
Trench	134.6	369.3	416.7	465.4	496.5	376.0
Mean	129.2	323.4	402.8	451.2	476.0	

Notes: SE/Plot: 88.0; general mean: 356.5; CV (%): 24.7 CD for (A): 57.1; CD for (B): 90.3; CD for (A) × (B): 127.7.

a. Planting Season. Two most important factors, which determine planting season, are topography and pattern of rainfall. Commonly planting is done in June–July months. Where southwest monsoon is torrential, planting is completed either before July or is taken up in August–September when the rains cease. Better crop establishment and growth are ensured through early planting as compared to late planting (Mayne, 1951a). In low-lying valleys planting should only be commenced after July when torrential rains begin to abate (Korikanthimath, 1980). In Mudigere district of the State of Karnataka, better establishment and crop growth were reported when the planting was done in the month of August (Pattanshetty and Prasad, 1972). Cardamom suckers are planted from June through August on the soil surface or 15- to 20-cm deep. With surface planting, mortality of seedling is least, and when rainfall is relatively less heavy in the week following planting. Suckers planted in August survived best, with a mean mortality rate of 25% and those planted on soil surface showed the lowest mortality rate of 17.5% (Pattanshetty *et al.*, 1972, 1974).

Investigations on the effect of monthly planting were carried at the Horticulture Research Station in Yercuad, Tamil Nadu, which is located on the eastern side of the Western Ghats along the State of Kerala. Planting was commenced from June through November during 3 years, to assess ideal planting time at elevations of about 1300–1500 m amsl. Best establishment (87.92%) was obtained in July planting, followed by August, September, October, and November planting with establishment rates of 77.9%, 75.4%, 63.7%, and 61.6%, respectively. June planting gave only 19.4% establishment. To obtain good establishment, a total rainfall of at least 322 mm has to be there, while the minimum and maximum temperatures should be in the range of 15.5–17.5°C and 19.5–25.0°C, respectively during the month of planting (Nanjan *et al.*, 1981).

b. Planting. The general practice is to scoop a small depression in the filled soil and the seedling is placed at the center of the depression. Soil is then replaced taking care not to disturb the roots in their normal position and pressed well around the base of the clump. Deep planting should be dispensed with as it results in suppressing growth of the young seedling and emergence of new shoots, which may lead to decay of underground rhizomes. Seedlings are normally planted at an acute angle to the soil level to prevent them being broken or blown by strong winds, which follow the planting season (Anon, 1952a). Light pruning is desirable, but this should only be confined to longer roots, avoiding shorter ones, of 0.3 m or more. In the case of rhizome planting, the planting material can be kept in pits in a slanting manner and rhizomes covered with soil as in the case of seedling planting. Following planting immediately, seedlings should be physically supported by stakes to prevent damage or being blown away by strong

wind and a mulch cover with dry leaves is provided at the base. Criss-cross staking with two stakes is the best practice to follow. Plants may be loosely tied to the stakes with dried banana sheath or jute threads to facilitate emergence and growth of aerial shoots. Care must be ensured to offset after transplantation shock, which emanates because of physical reasons, and the seedling must also be guarded against heavy rains. Unhealthy plants are prone to disease infestation, and it would be advisable to spray the seedlings with 1% Bordeaux mixture or any other suitable fungicide, as a prophylactic measure. The newly planted area should be inspected periodically and gaps when found should be filled instantly, if the climate is favorable.

c. Planting of Suckers. Propagating cardamom using suckers consists of splitting up established clumps into sections consisting normally of at least one old and one young shoot. Planting material of 20-cm long rhizome results in more shoots per clump, early bearing, and large net returns than short rhizomes of 2.5 cm (Pattanshetty, 1972a,b; Pattanshetty *et al.*, 1974; Pillai, 1953). The section of rhizome is placed in a small depression in a pit that is already prepared and covered over with soil and mulch. The leafy shoots are placed almost parallel to the soil surface. A clump is constituted by new shoots which arise from the rhizome. In the high ranges of Kerala State, straight planting of rhizome with stake is recommended. In Guatemala, propagation of cardamom is invariably by suckers, where the dreaded disease "Katte" is not a threat (Anon, 1977). Three suckers per pit are used to induce tillering in a short time span. Rapid growth and high-yielding pattern are the essential features of Guatemala which are mainly attributed to the conducive rainfall distribution pattern. Fertile soils and good plantation management complement this. In India also, farmers have realized high yields where intensive management practices have been resorted to, of which good irrigation is an important component.

d. Gap Filling. Good initial establishment is crucial to raising a productive cardamom plantation. On average, 5% gaps are seen in most cardamom plantations. Healthy and disease-free seedlings or clumps can reduce seedling mortality during establishment period. Monsoon failure during planting time is a potential hazard, in which case supplemental irrigation, once a week, is a must. It is advisable to use healthy, sufficiently grown up seedlings, or preferably clonal materials for filling the gaps. May–June, when monsoon starts, is the best time for gap filling. However, if this is missed, with proper care, gap filling can be extended up to August–September. Success of gap filling depends on after care until gap-filled plants reach the state of earlier established plants. Regular cultural operations must be carried out after planting, and these consist of regular mulching, weeding, trashing, raking/digging,

irrigation, shade regulation, manuring, gap filling, and plant protection measures to maintain plants in a healthy and vigorous condition.

e. ***Mulching.*** Cardamom productivity is very much dependent on proper moisture balance in the soil. In recent years in India, premonsoon showers have become quite erratic, on account of global warming. This results in cardamom plants facing drought even up to 6 months at a stretch. Mulching is a practical solution to conserve soil moisture, and has been acclaimed as the most important cultural operation for the overall improvement of soil and yielding capacity of cardamom plantations (Zachariah, 1976). Following are the advantages of mulching cardamom plantations.

1. By minimizing surface evaporation, soil moisture is conserved.
2. When rains occur soil does not get puddled because of the beating action of the raindrops, the physical condition of the soil is maintained.
3. It checks run off and erosion.
4. Both friability and soil structure are improved due to the enhanced biotic activity under the mulch. Soil becomes more porous as the number of macropores is increased by biotic activity. This helps in better water percolation and moisture conservation.
5. An equilibrium of soil temperature is maintained.
6. Enrichment of soil organic matter leads to enhanced biotic activity with its positive fallout on nutrient availability and soil fertility in general.
7. Weed growth is controlled.
8. Results in better root growth, which in turn, leads to extraction of soil moisture from deeper layers.
9. Eventual decomposition of the mulch affects soil fertility eventually.

Soon after planting, base of the plants is adequately mulched. Mulching is a simple cultural operation in which dried leaves and other plant residues are used. The mulching should be completed before the onset of summer. Leaves shed by the shade trees come in handy for mulching which can de done in the months of November–December. An investigation was conducted to study the relative merit of locally available mulching materials such as dried leaves, paddy husk, phoenix leaves, coir dust, and stratified leaf mulch under uniform shade of coir matting and by using suckers of cv. P1 combined with two levels of irrigation, namely, 75% and 25% available moisture. Results are in Table XVII. Results did not show any significant difference on production of suckers due to irrigation levels. Leaf mulch and phoenix leaves were at par, statistically, but were found to be significantly superior to other mulches in the production of suckers (Raghothama, 1979).

Demulching is equally important and should be carried out in May after the premonsoon showers to facilitate honeybee movement in the plantations, which will ensure better pollination and capsule setting. The practice of

Table XVII
Effect of Different Mulch Materials on Germination of Cardamom Seeds

Treatment	Germination (%)	Leaf spot disease (%) 45 DAS
Paddy straw	40.8	12.0
Dry leaves of rose wood	37.4	16.2
Paddy husk	27.2	23.6
Saw dust	33.6	12.8
Wild fern	38.2	14.5
Coffee husk	21.6	25.6
Charcoal	35.2	19.2
Polythene sheet	1.8	–
Phyllanthes emblica leaf twigs	37.1	17.3
Sand	12.2	–
Control	13.3	–
SE/plot	4.3	5.9
General mean	27.1	12.8
CV (%)	15.9	46.4
LSD ($p = 0.05$)	6.2	8.6

Note: DAS, days after sowing.

uncovering the panicles shortly after the commencement of flowering improves fruit set. Average number of capsules per plant is 27.4 and 2.1, respectively in the case of exposed and covered panicles in variety Malabar (Pattanshetty and Prasad, 1974). The removal of mulch, which accumulates in the center of the clump and thereby releasing panicles beneath, would not only facilitate movement of honeybees, but will also provide better aeration and minimize incidence of clump rot and rhizome rot disease.

4. Weed Control

Since the cardamom plant gets its nutrition from the top layers of the soil, it is crucial that in the first year of planting frequent weed control is done to avoid root competition between young cardamom seedlings and weed, as both can compete for nutrients and moisture. Weeding is carried out either on the entire area covering the plants or on just around the plants. It is called ring weeding. The weeds are used as mulch for young plants. As many as 21 dicotyledonous weeds are identified in cardamom estates in the Coorg district of Karnataka State. Of these, *Strobilanthes ureceolaris Gamb* is the most common. Weeds are controlled mainly by hand weeding, only in rare instances are chemicals used. Two to three rounds of weeding are essential in the first year of planting to remove regenerating undergrowth. Generally, first

hand weeding is done in the months of May–June, the second in August–September, and the third in December–January. When weeding is done in May–June and August–September, the weeded matter are heaped in the inter-row spaces and are later used for mulching. In November–December when the weeding is done, the matter is directly utilized for mulching. Slash weeding is the most common in cardamom plantations. Spraying Gramaxone at the rate of 1.5 ml liter^{-1} twice a year is also resorted to in some plantations, although infrequently, and this practice is quite economical and convenient.

5. Additional Field Operations

These are trashing, raking, digging, and earthing up. Trashing consists of removing old and drying shoots. Beginning second year of planting, trashing has to be continued every year. Trashing promotes better sunlight penetration and aeration, thereby promoting tiller initiation and plant growth as well as reduction in thrips and aphids infestation. It also helps in better pollination by honeybees (Korikanthimath and Venugopal, 1989). In rainfed areas, trashing time is May, after the receipt of premonsoon showers. The trashed leaves and leafy stems may be heaped between the rows and allowed to decay or used for composting. A light raking or digging of soil around the clump up to a radius of 75 cm is done toward the end of the monsoon. The soil mulch formed around the plant base helps conserve moisture during the following period. This practice is particularly useful in low-rainfall areas. Digging not less than 25-cm deep, once in alternate years, may be done in the entire area, followed by the application of farmyard manure or any other organic manure, such as bone meal, stera meal, groundnut cake, and so on. Digging can also be done in patches; it is, however, necessary to dig each year if the soil is clayey (Kuttappa, 1969b). Toward the end of the rainy season a thin layer of fresh and fertile soil rich in organic matter may be spread at the base of the clump which covers up to the collar region. This soil is obtained by scraping in between the rows or collecting the same from the trenches or pits. The thin layer of soil applied in the center of the clumps will not only keep them intact and cover the exposed roots, but also will check the "walking" habit (radial growth) of the cardamom plant (Korikanthimath and Venugopal, 1989). Care must be taken not to heap the soil above the collar region of the clump.

6. Replanting in the Plantation

Decline of yield is a problem in cardamom, although it is a perennial crop. Once in 8–10 years, regular replanting has to be done to ensure high productivity. One of the main reasons for low-average cardamom yield in India is on

account of the fact that there are many old plantation where no replanting has ever been made (Korikanthimath *et al.*, 1989). Clonal material from superior high-yielding varieties may be used for replanting, which will ensure that the yields are high. Korikanthimath *et al.* (2000a) investigated the economics of replanting. The authors replanted a cardamom plantation after a period of 10 years using the trench system of planting and maintained the replanted plantation with all the recommended inputs—fertilizers, irrigation, and so on—as per the package of practices recommended in the "high-production technology" (HPT). Planting materials used were 10-month-old seedlings from high-yielding mother plants. The replanted field gave 155 kg of dry cardamom in the second year. In the following year a record yield of 1775 kg ha^{-1} was obtained. In the subsequent 3 years dry yield obtained was 385, 560, and 870 kg ha^{-1}, which averaged 749 kg ha^{-1} $year^{-1}$. Economic analysis carried out by Korikanthimath *et al.* (2000b) showed a net return of Rs 2, 03, 465 ha^{-1} (which is approximately US$4800 at current rate of US$–Indian rupee exchange) and the benefit–cost ratio (BC ratio) worked out to 2.78. The investigation conclusively demonstrates that replanting a cardamom field after a 10-year gap is economically advantageous.

7. Propagation

Both by seeds and through vegetative means can cardamom be propagated. Seedling population is variable because cardamom is a cross-pollinated crop. Hence, vegetative propagation is only adopted in the case of elite clones. Both micropropagation (tissue culture) and rhizome bits (suckers) can be used for vegetative propagation. With commercialization, micropropagation has become quite popular in cardamom production.

8. Propagation Through Seeds

In order to obtain quality seedlings, cardamom nursery has to be managed carefully and scientifically. This involves sowing seeds on raised beds, transplanting into primary and then on to secondary nursery beds and finally into the field (Cherian, 1979; Kasi and Iyengar, 1961).

9. Seed Selection

Seeds should be collected from high-yielding vigorous plants, with well-formed compact panicles and well-ripened capsules free of pest and disease infestation. Number of flowering branches formed on the panicles, percentage of fruit set, and number of seeds per capsule should be given due consideration

while selecting the number of plants for seed collection (Anon, 1979; John, 1968; Ponnugangum, 1946; Siddaramaiah, 1967; Subbaiah, 1940). Apart from these desirable attributes, the mother clump should have more number of tillers (shoots) per plant, leaves with dark green color, and high percentage of fruit set. Color of capsules should be dark green (Krishna, 1968). On average, 1 kg of fruits contain 900–1000 capsules with 10–15 seeds per capsule. Taking into consideration the percentage of germination, mortality due to diseases, and so on, on an average 1 kg of seed capsules are required to obtain about 5000 plantable seedlings.

10. Preparation of Seeds

Seeds for sowing are collected from fully ripe capsules preferably from second to third round of harvest and are then either washed in water or sown immediately or mixed with wood ash and dried for 2–9 days at room temperature. The first method gives better results and is adopted widely. Following picking, seed capsules should be immersed in water and gently pressed for separating seeds and washed well in cold water to remove mucilaginous coating on the seeds. After draining water, seeds should be mixed with ash and surface dried in shade.

11. Viability of Seeds

Stored seeds lose viability over time, and this would result in delayed germination, or sometimes, no germination at all. Seed germination was found to be 59% and 50.6% in varieties Mysore and Malabar, respectively (Korikanthimath, 1982). Germination was reduced when stored seeds were used, especially those stored in airtight containers. Seeds treated with organomercurials and stored in open bottles would germinate up to 4 months. Highest germination of 71.8% was observed when sowing was done in September (Pattanshetty and Prasad, 1973; Pattanshetty *et al.*, 1978). In a clone of variety Malabar germination gradually declined. Seeds sown 60 days after storage, at fortnightly intervals starting August up to 14th of October, showed progressive decline in germination—56.7%, 51.0%, 46.4%, 34.1%, 32.5%, and 29.6%.

When sown immediately after in September, germination was uniform and early and are ready for transplantation at the end of 10 months. If they are further retained in nursery beds for the next planting season either by proper thinning or by transplantation at wider spacing in secondary nursery beds, they develop rhizomes with large number of tillers and are ideal for field planting (Pattanshetty and Prasad, 1972). November–January has been

found to be the ideal sowing time for Kerala State and for Tamil Nadu and Karnataka, it is September–October (Anon, 1970, 1979).

12. Presowing Treatment of Seeds

Cardamom seed possesses a hard seed coat, which delays germination. Investigations have been carried out to study the effect of presowing treatments of seeds to offset delay in germination. Treatment of freshly extracted seeds with concentrated nitric acid or hydrochloric acid for 5 min significantly improved the germination of seeds sown during November (Pattanshetty and Prasad, 1974; Pattanshetty *et al.*, 1978). Treating the seeds with 20% nitric acid, 25% acetic acid, and 50% hydrochloric acid for 10 min was found to show 97.6%, 98.6%, and 91.5% germination, respectively. Korikanthimath (1982) found treating with 10% nitric acid to be the best for enhancing generation. Ambient temperature also plays an important part in germination. Low ambient temperature in the winter in cardamom-growing areas not only reduces germination but also delays it (Krishnamurthy *et al.*, 1989a). Gurumurthy and Hegde (1987) found that germination is significantly correlated with maximum and minimum temperatures prevalent in the area.

13. Nursery Site

It is always preferable to select nursery site on gentle slope which has an easy access to a perennial source of water. The nursery area should be cleared of all existing vegetation, stumps, roots, stones, and so on. Raised beds are prepared after cultivating the land to a depth of about 30–45 cm. Usually beds of 1-m width and convenient length and raised to a height of about 30 cm are prepared for sowing the seeds. A fine layer of humus rich forest soil is spread over the beds. The beds, when treated with formaldehyde solution (4%) are found to control "damping off," another important disease of cardamom (Anon, 1985). After this treatment the beds are covered with polythene sheets for a few days and seeds are sown 2 weeks after treatment. Before sowing, beds have to be flushed with water to remove any remaining formaldehyde.

14. Seed Rate and Sowing

The seed rate is 2–5 g to raise 10-month-old seedlings and 10 g to raise 18-month-old seedlings (Anon, 1976, 1986). Seeds are sown in lines, usually not more than 1-cm deep. Rows are spaced 15 cm apart and seeds are sown 1–2 cm apart within the row. For better and quicker germination deep sowing should be avoided. Lindane at the rate of 60 g/5 m^2 is to be used to dust seedbeds to

prevent termite attack. After sowing a thin layer of sand or soil is spread over the beds and pressed gently with a wooden plank, and a thin mulch of leaves may be provided. Thereafter beds are to be watered everyday. Germination will start after 1 month and may continue for a month or two more. Soon after germination commences, the mulch is removed and shade is provided to protect the young seedlings from direct sunlight and rain.

15. Mulching of Nursery Beds

Germination is influenced by mulching (Abraham, 1958). Using locally available mulch materials, Korikanthimath (1980) carried out investigations on the effect of mulches on germination. The materials used were paddy straw, paddy husk, dry leaves or rose wood tree, saw dust, wild fern, coffee husk, goose berry (*Phyllanthes emblica*) leaves, sand, charcoal, polythene sheet. Maximum germination (40%) was observed in the case of paddy straw mulch when seeds were sown in September and this treatment was statistically at par with that of rose wood tree dry leaves (37%) and wild fern (38%, refer Table XVIII). There are also other reports which show that mulching with coconut coir dust, paddy straw, or goose berry leaves enhances germination (Korikanthimath, 1983a; Mayne, 1951a; Sulikeri and Kologi, 1978).

16. Secondary Nursery

In the States of Kerala and Tamil Nadu, the seedlings are transplanted to secondary nursery beds when they are about 6-month old, whereas in the State of Karnataka, the practice is to sow the seeds in the primary nursery and

Table XVIII
Mean Cardamom Yield (g per Plant) Under Different Shade Trees

Name of the shade tree	Year				Mean yield
	1975–1976	1976–1977	1977–1978	1978–1979	
Karimaram	112	81	81	207	121
Elangi	82	62	46	126	79
Jack	66	65	52	135	79
Nandi	109	65	42	135	89
Mean yield	92	68	55	151	92

Note: SE for species = 57.5, CD; LSD $p = 0.05 = 18$.
SE for years = 49.4, CD; LSD $p = 0.05 = 15$.
CD for any 2 years for any species = 31; CD for any two species for any years = 32.

thin the seedlings out to the required stand, which allows them to grow in the same place. Transplanting seedlings to secondary nursery reduces nursery diseases. Korikanthimath (1982) has demonstrated that following both primary and secondary nursery practices would be needed to get vigorous seedlings which have four to five within a span of 10 months and having lesser disease and pest incidence. On an average, 10 secondary seedbeds are required to transplant seedlings from one bed. Secondary nursery beds are made the same way as the primary ones. A mixture of powdered dry cattle dung and wood ash is spread over the secondary seedbeds before transplanting seedlings. In Karnataka, where seeds are sown in August–September, transplantation or thinning is done in November–January. In Kerala State and Tamil Nadu seedlings from primary beds are transplanted to secondary beds at a spacing of 20 cm × 20 cm in June–July. Seedling mortality rate was found higher in the case when transplantation was done at second leaf stage (25.4%), while in the case when transplantation was done at the fifth leaf stage, mortality was 1.1%. Number of seedlings produced was more at wide spacing of 30 cm × 30 cm (11.9) when compared to narrower spacing of 22.5 cm × 22.5 cm (9.2) or still narrower spacing of 15 cm × 15 cm (7.3). However, in view of the larger area and higher expenditure involved in raising nurseries when transplantation takes place at 5–6 leaves stage, a spacing of 15 cm × 15 cm is recommended (Korikanthimath, 1982).

17. Manuring

Generally organic manure, such as well-decomposed compost, cattle manure, fertile top forest soil, and so on, are used for application to each seed bed at the rate of 8–10 kg/25 m^2 land area both in the case of primary and secondary nurseries. From a seedbed planted with 100 cardamom seedlings, it was found that, on average, 120 g N, 20 g P, 300 g K, 50 g Mg, and 75 g Ca are removed, which shows that cardamom is a heavy feeder of K. Hence, K nutrition needs special attention. To facilitate uniform growth, 250 g mixture made of nine parts of NPK in the ratio of 17:17:17 and eight parts of zinc sulfate dissolved in 10 liter water is sprayed once in 15–20 days starting from month one after transplantation (Anon, 1990). Regional Research Station in Mudigere, in Karnataka State, recommends NPK mixture at the rate of 160 g per seedbed 1 month after planting. This is to be increased by 160 g every month until a maximum of 960 g per bed is reached. The NPK mixture consists of one part urea, two parts super phosphate, and one part muriate of potash (MOP) (Anon, 1979). Application of 45 g N, 30 g P_2O_5, and 60 g K_2O per bed of 2.5 m × 1 m size in three equal splits at an interval of 45 days would result in better growth and higher tiller number (Korikanthimath, 1982). The first dose of fertilizer is applied 30 days after

transplantation in the secondary nursery. Application of diammonium phosphate (DAP) along with MOP was found to enhance root growth and tiller production (Anon, 1989).

18. Overhead Shade

The young seedlings must be protected from the heating of the direct impact of sunlight for which overhead shade has to be provided. A framework erected with wooden poles and sticks and spreading a sheet of nylon nursery sheet or coconut frond can be used for the purpose of providing shade. Ideally, 50% shade has to be provided and this helps better tiller formation and growth. When monsoon starts, the shade nets have to be removed.

19. Irrigation and Drainage

Up to 8–10 days after transplanting, nurseries should be irrigated twice daily and thereafter once up to 30 days. Once the seedlings establish and put forth fresh growth, irrigation may be done on alternate days until monsoon sets in. Flood and splash irrigation must be avoided as it would create conditions for the onset of "damping off" and leaf diseases. Stagnation in the nursery should be avoided by proper drainage. In low-lying areas central and lateral drains should be provided to prevent water stagnation.

20. Weeding

Until the plants grow sufficiently big, which will smother undergrowth of weeds, hand weeding is the best practice to keep the nursery clean, and it should be done at an interval of 20–25 days.

21. Earthing Up

The top soil between the rows of cardamom seedlings would normally get washed away and deposited in pathways when rains commence. To prevent this, scraping of soil from pathways and application of a thin layer of soil up to the collar region of the plants may be taken up 2 months after transplanting in the secondary nursery. Fertile soil application collected from the forest along with cattle manure would be beneficial. Earthing up may be taken up immediately after split application of fertilizers.

22. Rotation and Fallow in Nursery Site

Ideally, nursery sites should be shifted once every 2–3 years to prevent build up of pathogens in the soil. If shifting is not feasible, it would be advisable to grow a short duration green manure crop like Crotalaria or Sesbania which will enrich the fertility of the nursery site through organic matter build up and mobilization of plant nutrients. These green manure crops must be ploughed into the soil. Fallowing for 1 year can also be done in partial nursery area, which has the positive effect of rejuvenating the soil and also control any buildup of insects or other pathogens in the soil. Sunlight falling directly on fallowed land has the effect of sterilization.

When all of the above cultural practices are followed, seedlings would be ready for transplantation in about 10 month's time after sowing of the seeds. Raising seedlings in primary nursery and subsequent transplantation in secondary nursery is found to be more advantageous, as it facilitates better establishment and initiation of adequate number of suckers per plant.

23. Paddy Fields as Nurseries

In the State of Karnataka, small and marginal cardamom farmers in the districts of Chickmagalur, Coorg, and Hassan raise nurseries in wet paddy fields. The most important precaution when this is done is to provide good drainage to avoid water stagnation. Beds are separated by deep channels. The wet paddy soils are heavy and this leads to excessive moisture in soil, and this could hamper good seedling establishment and emergence (Mayne, 1951a).

24. Dry Nursery

The Malay system of cardamom production employs the dry nursery technique, and this is practiced in the Coorg district of Karnataka State. The forest cover provides good shade, and there is no need to irrigate as frequently as in the case of open fields. As no irrigation is involved, the technique is called the dry nursery. Nursery operations are limited. After initial showers in April, dry seeds are broadcast where leaf litter is heaped. Seeds are raked into the soil and the surface is covered with leaf mould. The branches of trees are cut to regulate overhead shade. After germination hand weeding is done. Before the monsoon fully recedes, forest soil is spread over the seedbeds, and leaf litter is also spread over. Seedlings withstand drought while growing. These seedlings are planted in the main field after attaining sufficient growth, as in the other case of seedlings raised conventionally.

25. Polybag Nursery

Polyethylene bags (20 cm × 20 cm) and 200–300 gauge thickness with six to eight holes can be used for raising cardamom seedlings. These bags are first filled with nursery mixture in the ratio of, 3:1:1 (forest top soil, farmyard manure, and sand, respectively). The bags are then arranged in rows of convenient length and breadth for easy management. Seedlings of 3–4 leaf stage can be transplanted into bags. Subsequently, adequate space is left in between bags to facilitate better tillering. Seedlings obtained in this manner are uniform in growth and subsequent tillering and establish better in the main field, and the main advantage is that nursery growth time can be substantially shortened. An investigation carried out at the Cardamom Research Center, Appangala, Karnataka State, on the relative merits of raising seedlings in the conventional manner and in polyethylene bags showed that in the main field 30 days after transplantation, there was 6% mortality of seedlings in the former compared to just 1% in the latter. The high cost of raising seedlings in polyethylene bags and their transportation preclude the practice from following in large plantations, while the method is suitable in the case of small or marginal cardamom planters, homestead gardens, and also small estates.

26. Cost of Raising Seedlings

Duration of the nursery and age of the seedlings determine the cost of raising a cardamom nursery. The thumb rule is one season equals 10 months, and 18–22 months equal two seasons. To raise 100,000 seedlings of 10 months age, an expenditure of approximately Rs 84,723 (approximately US$ 1980 based on current Indian Rupee–US Dollar exchange rate) is required. Usually increasing the number of seedlings can bring down cost of seedling production. The Spices Board of India supplies seedlings at the rate of approximately 7 US Cents (Rs 3 per seedling). It would be around Rs 4–4.50 for an 18-month-old seedling that is about 10 cents.

27. Age of Seedlings for Field Testing

The factors considered important in selecting the age of the seedlings, either one season (10 months) or two seasons (18–22 months) are, first, the comparative success of establishment of the seedlings in the estate (cardamom plantation) and also the cost of raising the seedlings. One-year-old seedlings can be good for new planting, while 2-year-old seedlings with a well-developed rhizome would be more suitable for gap filling. Seedlings,

18–22 months old, usually are preferred for planting in the State of Kerala and Tamil Nadu (Kasi and Iyengar, 1961).

28. Seed Propagation and Its Disadvantages

Since cardamom is a cross-pollinated crop, seedling population will be highly heterogeneous, and the average yield from such plantations will be generally low. Only 36% of the plants are good yielders in a plantation raised from seedlings, as per the findings of a survey (Krishnamurthy *et al.*, 1989a). Another study of a population of 1490 plants from seedlings has shown that 45% of the plants are poor yielders (less than 100 g of green capsules per plant) contributing only 12.5% of the total yield. About 36% are medium yielders contributing 40% of the total yield. Good yielders are about 15% which contributes 32.1 of the total yield; in this group, plants which give high yield (500–900 g) were hardly 4% but contributed 15% of the total yield. Average yield of this experimental population was 170 g green capsules per plant. The high degree of variability in yield and high percentage of poor yielders in the seedling population necessitates selection of the elite clones and their vegetative propagation.

29. Vegetative Propagation

To establish plantations of high productivity, suckers of elite clones should be used. There are methods to achieve high rate of sucker multiplication of selected high-yielding clumps (Anon, 1978). Plants raised from rhizomes come to bear earlier than those from seedlings. Clonal propagation is also followed in Guatemala (Anon, 1977). Using tillers (suckers) and micropropagated tissues (Kumar *et al.*, 1985) can be resorted to raise cardamom plants. Small-scale farmers in the States of Kerala and Tamil Nadu use suckers. In areas where the deadly virus disease "Katte" is prevalent, use of suckers should be dispensed with. The nonavailability of high-yielding selections is one of the important constraints to achieve high yield in cardamom. Attempts have been made at various cardamom research stations in India to select high-yielding lines (Korikanthimath, 1998). In one such attempt, 80 clumps yielding more than 400 g of green capsules per clump were selected, each clump divided into four sets, and the yield performance of 320 plants investigated during a 6-year period. About 42% of the good yielders contributed 43% of the yield and 17% of the very good yielders contributed 34% of the yield, which indicates that the average yield of the population can be improved significantly through the use of suckers (Parameshwar *et al.*, 1989). Such studies led to the development of clonal propagation techniques that are

fairly rapid. Clonal multiplication through tissue culture has also been standardized (Kumar *et al.*, 1985).

30. Rapid Clonal Nursery Technique

A quick method of proliferation of suckers was developed at the Indian Institute of Spices Research administered Cardamom Research Center at Appangala, Karnataka State, to generate more number of planting units targeting high yield in a short time span by resorting to high density planting in trenches, closely spaced, under controlled overhead shade (Korikanthimath, 1992, 1999). Following are the steps involved in the process.

1. Pest and disease free plants, with bold capsules marked and part of the clump uprooted for clonal multiplication leaving the mother clump in its original site to induce subsequent suckers for further use.
2. Each planting unit consists of one grown up sucker and a growing young shoot.
3. The planting units are spaced 1.8 m × 0.6 m in trenches, which accommodates approximately 6800 plants per hectare of clonal nursery area.
4. On average, 32–42 suckers per planting unit will be produced in 12 months after planting; after 1 year it is possible to obtain 16–21 planting units from one clump.
5. In 1 ha of clonal nursery, 1- to 1.4-lakh (100,000–140,000) planting units can be produced after 1 year.
6. A crop of 190 g per plant dry cardamom (1759 kg ha^{-1}) was harvested within 19 months of planting (from planting date to harvest) (Korikanthimath, 1990, 1992). The system is cheap to set up and easy to manage.

E. Shade Management in Cardamom

Cardamom is very sensitive to moisture stress and performs comparatively better in cool, shady environment. The shade canopy provides suitable environment by maintaining humidity and evaporation at suitable level (Abraham, 1965). Cardamom does not tolerate direct sunlight, so also, it cannot do well under excess shade, since metabolic activities are impaired owing to inadequate light penetration. Shade has to be regulated based on the lay of the land and moisture retention, and so on, to obtain 50% of filtered sunlight for growth and flowering. Following beneficial effects of shading in cardamom plantations should be noted.

1. Good canopy and cool temperature are maintained which protect the soil from the scorching effect of the sun. Shade also checks surface evaporation of soil moisture, thereby helping moisture retention for a longer period, which is important to realize good yield.
2. Protects plants from sun-scorching. On the border rows, where sunlight falls directly, pest infestation has been noticed.
3. Checks high velocity of rainfall and minimizes mechanical damage to plants, like splitting of leaves.
4. The network of root system of shade trees prevents soil erosion and protects soil loss due to the beating action of rains, which leads to improvement of the physical properties of the soil.
5. Maintains adequate humidity and soil moisture, which are essential for proper growth, flowering, and capsule set.
6. Build up sufficient humus and organic matter and soil fertility through the addition of leaf litter.
7. Act as a wind break and minimizes ill effects of gale and heavy wind.
8. One or the other shade trees flower round the year and thus act as an alternate source of nectar to honey bees, which are the principal pollinating agents of cardamom. Forest areas ensure foraging capacity and availability of nectar for a long period.
9. Shade trees provide congenial microclimate for proper growth and performance, help in checking weed growth, which otherwise would grow luxuriantly in open areas and their control then would be major problem.

1. Ideal Shade Trees

In forest all kinds of trees are found, and they come in handy as shade trees. In the cardamom hills of Kerala State, Karnataka State, and Tamil Nadu, trees belonging to 32 families of Angiosperms constitute the major tree flora (Shankar, 1980). An ideal shade tree in cardamom plantation should possess the following characteristics.

1. A wide canopy to minimize the number of trees required for shade.
2. No flower shedding during pollination period so that pollination is not adversely affected.
3. Trees should be of medium size, evergreen which retain their foliage throughout the year.
4. Trees should have small leaves and a well-spread branching system.
5. To avoid competition for nutrients and water, the trees should be deep rooted.
6. Trees must be fast growing to provide immediate and required shade.
7. Trees must have hard heartwood to withstand high-velocity winds.

A mixed population of medium-sized trees, which facilitate shade regulation and maintain more or less optimum conditions through the year, is desirable. The principal trait to be looked into while selecting shade trees is adaptability to the local climate, growth rate, and ease of establishment. Among the common trees, Balangi (*Artocarpus fraxinifolius* Wt), Nili (*Bischofia javanica* Blum), Jack (*Artocarpus heterophyllus* Lamk), Red cedar (*Cedrella toona* Roxb), Karimaram (*Diospyros ebenum Koenig*), Karna (*Vernonia monocis* C.B. Darke) are desirable as shade trees for cardamom (Abraham, 1957; Rai, 1978). An introduction from Africa, *Maesopsis eminii*, is a very good shade tree (Korikanthimath, 1983). Another introduction is silky (silver oak), *Grevellia robusta* and this tree is now a very popular shade tree as well as stake for Black pepper. The wood is hard and is a useful cabinet wood. Heterogeneity of shade tree species and their characteristics is the major constraint to conduct investigations on shade requirements of cardamom. Certain studies have been carried out to evaluate the usefulness of existing shade trees and identify the most useful for cardamom (George *et al.*, 1984). In this investigation, four important species, such as Karimaram or ebony, Elangi (Spanish Cherry, *Mimusops elangi*), Nandi or beatrack (*Lagerstroemia lanmceolata*), and Jack, have been evaluated. Results indicated that cardamom plants grown under Karimaram produced significantly more number and longer panicles and longer leaves, yielding 40–50% more than those plants under other shade trees (Table XVIII).

Trees that carry crowded crown canopy are undesirable as shade trees as they hardly allow filtered sunlight. *Erythrina lithosperma* and *Erythrina indica* (Dadaps) are commonly planted by growers, especially when cardamom is planted in low-lying areas but they are unsuitable as they compete for nutrients and soil moisture (shallow rooted) and act as an alternate host for nematodes.

2. Shade Requirements

Requirement for shade varies from place to place depending on the lay of the land, soil type, rainfall pattern, crop combination, and so on (Abraham, 1965; Korikanthimath, 1991). In Guatemala, which receives well-distributed rainfall and has a cool climate round the year, cardamom is grown practically in open areas with either no shade or having only very sparse shade (Anon, 1977). This is a major factor contributing to higher productivity in the country.

Gaps in the shade canopy have almost always led to leaf scorching in Indian conditions. It appears that the performance of cardamom plants under Indian conditions depends on their interaction with shade, sunlight, and soil moisture (Aiyappa and Nanjappa, 1967). Sulikeri (1986) in an

investigation on light intensity and levels of soil moisture on growth and yield of cardamom reported that under high-density planting (9000 plants ha^{-1}), yield was 1873 and 1928 ha^{-1} under medium (40–45%) and high (65–70%) light intensity respectively, as against 864 under low light intensity (15–20%, Table XIX). Heavier capsules (75.6 g per 100 capsules) were produced by plants receiving medium light intensity compared to those receiving high light intensity 72.3 g per 100 capsules) and low light intensity (71 g per 100 capsules). Harvest index (HI) under medium light intensity was 0.073 as against 0.066 under low light intensity and 0.037 under high light intensity. This simply shows that it is important to regulate light intensity, especially during rainy season, where overcast sky reduces light intensity. It is equally important that shade trees put forth sufficient foliage and provide adequate shade by the time summer sets in. The overhead canopy should, therefore, be regulated once a year during May–June. With the denudation of forests in the Western Ghats, the normal ecosystem is destabilized and the microclimate and rainfall pattern in the cardamom-growing tracts are vastly changed. On the onset of the dry season (November–January) cool and humid microclimate in the plantation changes rapidly as hot air wave from the hinterlands pass across the cardamom tracts without much hindrance due to deforestation all around cardamom pockets. As a consequence, cardamom plants face inclement environment thereby resulting in poor growth and consequent yield. Owing to high wind velocity, the transpiration and evaporation rates will be increased. Moreover, plants suffer due to physical pull of the blowing of high-velocity wind. The enhanced evaporation and transpiration deplete soil moisture rapidly.

3. Pest Outbreak in Relation to Shade

The ecological upsets, especially the edaphic ones, have triggered the pest problems in cardamom plantations. This is a consequence of the so-called "green revolution," where the indiscriminate use of chemicals, both fertilizers and pesticides, in the soil environment, has led to many environmental related problems and the outbreak of pests, that was once considered minor, is assuming alarming proportions in many cardamom-growing areas. Among the insect pests, root grub is seen in exposed, warm, and less shaded conditions and the insect has emerged as a major pest of cardamom in many areas (Gopakumar *et al.*, 1987). White flies likewise, are threatening the cardamom plantations in many areas. Outbreak of locusts in Udubanchola taluk in Idukki district of Kerala State is another example of the ill effects of changes in the microclimate (Joseph, 1986).

Table XIX
Dry Yield of Cardamom (kg/ha) as Influenced by Varying Light Intensity and Soil Moisture Levels

	Light intensity			
Moisture levels	Low (5000–7000 Lux)	Medium (15,000–17,000 Lux)	High (25,000–27,000 Lux)	Mean yield
Control	706.50	1217.25	645.75	856.50
Water at 25% ASM	945.90	2030.22	2521.53	1832.55
Water at 75% ASM	941.22	2373.03	2618.88	1977.51
Mean	864.54	1873.50	1928.52	1555.52
Treatment effects	Significance	LSD ($p = 0.05$)	LSD ($p = 0.01$)	
Main treatment	**	366.84	521.82	
Subtreatment	**	221.49	298.26	
Interactions				
(a) Two levels of subtreatments at a fixed level of main treatment	**	383.58	510.60	
(b) Two levels of main treatments at a fixed level of subtreatment	**	492.21	685.35	

Note: ASM, available soil moisture; **, significant at LSD ($p = 0.05$); main treatment refers to moisture levels; subtreatment refers to light intensity.

4. Biorecycling

Among the plantation crops, no other has this benefit through the maintenance of tree growth *in situ* as cardamom has. As soil applied nutrients are liable to leaching and loss, trees absorb them and cardamom is a good example. Leaf fall affects a recycling process of these minerals to upper soil layer enriching soil fertility in the process.

5. Water Requirements and Irrigation Management

In general, cardamom is grown as a rainfed crop, and cardamom-growing regions experience a dry spell of about 5–6 months in a year. Increased denudation of forests, deterioration in forest ecology, coupled with erratic trends of rainfall leads to aridity effects and adversely affects cardamom production (Ratnam and Korikanthimath, 1985). Even if there is no reduction in total rainfall, failure of premonsoon and postmonsoon showers affects the crop adversely. During monsoon, postmonsoon, and winter months, although there is sufficient moisture in the soil, plant growth is rather slow because of low ambient temperature. During summer months, if adequate moisture is available, cardamom plant puts forth luxuriant growth. Under normal conditions, panicles start emerging during January and continue to produce flowers from May onwards. When postmonsoon rains fail and moisture stress precipitates, flower drop occurs and fruit set is hampered. Under severe conditions of moisture depletion, drying up of panicle tips occurs. Therefore, irrigation is necessary from January through May. In such a situation, determination of adequate moisture for higher yield of cardamom needs no emphasis. Raghothama (1979) studied the effect of mulches and irrigation on sucker production using two levels, 25% and 75% available soil moisture (ASM). There was no separate control treatment in this investigation. Irrigation at 75% ASM showed enhanced performance of all growth and yield parameters, including cardamom yield, but there was no statistical difference between this treatment and 25% ASM. The differential effects of the moisture level treatments were nullified by the effect of mulching treatment and also due to reduction in dry spell. Plants at higher irrigation level (75% ASM) produced more and longer panicles, more number of internodes, higher number of capsules, more fruit set, and higher capsule weight

Although cardamom requires high moisture level, it is very sensitive to high water table and consequent water logging (Sulikeri *et al.*, 1978). For better growth, drains should be opened at regular intervals so as to keep the water table 30 cm below surface. Sulikeri (1986) investigated the effect of light intensity and moisture level on the growth and yield of cardamom. Results are in Table XIX. They indicate that irrigation at 75% ASM resulted in the

maximum yield of 1977 kg ha^{-1} which was more by 8% (1832 kg ha^{-1}) compared to irrigation at 25% ASM and 31% more than that in the control treatment. Light intensity had a very positive effect and high light intensity (25,000–27,000 Lux) increased yield by 123% compared to low intensity light at 5000–7000 Lux. It is also seen that in the control treatment there was yield depression at the highest light intensity (25,000–27,000 Lux) compared to low light intensity at 5000–7000 Lux. In the medium light intensity level at 15,000–17,000 Lux, yield in the control peaked indicating that high light intensity might, indeed, be detrimental when the other factors of production are missing.

6. Irrigation Methods

Among the different systems of irrigation, such as surface, subsurface, overhead, trench, and sprinkler, the last one is most ideal in the case of cardamom plantations.

7. Sprinkler Irrigation

Overhead irrigation with sprinklers has many advantages. Cardamom is grown on hill slopes with undulating topography and for such land, sprinkler system can provide uniform water supply. Since the rate of water supply can be regulated, surface loss due to run off and evaporation and conveyance loss also are greatly minimized (Anon, 1985; Bambawale, 1980; John and Mathew, 1977; Saleem, 1978; Vasanth Kumar and Sheela, 1970). This will also preempt puddling, leaching, and run off which are common with other irrigation systems. The humid atmosphere required for the successful growth and production of cardamom can be created by overhead sprinkling. Frequent light sprinkling can be done in soils of poor water-holding capacity. Irrigation equivalent to a rainfall of 4 cm, every fortnight would be quite sufficient.

Installation of a sprinkler system should be processed after a careful survey of the area for efficient and economical design. A perennial source of water is required nearby. Sprinkler systems are designed to meet specific requirements, which may vary from one plantation to another depending on the lay of the land, area to be irrigated, and source of water. The pumping site should be selected in a convenient place which should cover the entire area with least number of pipes. Portable units are more economical to use but operation costs are slightly higher compared to the permanent system. The main line and laterals can be made portable so that they can be moved easily from one position to another.

Vasanthakumar and Sheela (1970) conducted field investigation on sprinkler system for two consecutive years. The field design was a split plot, with irrigated and nonirrigated treatments as main plot and cardamom varieties, Malabar, Mysore, and Vazhukka, as subplots. Results are in Table XX. Results indicate that var. Vazhukka produced the highest panicle number per clump (114.6) in the irrigated treatment compared to nonirrigated one (90.8). Variety Mysore produced the least panicles in the nonirrigated treatment (51.8). All cultivars produced more flowers in sprinkler irrigated plots (3048, 1894, and 3754 respectively in varieties Malabar, Mysore, and Vazhukka, respectively) compared to the nonirrigated plots (26.4, 26.3, 27.6 in varieties Malabar, Mysore, and Vazhukka, respectively). Capsule shedding was comparatively low in the irrigated plots (14.5%, 14.9%, and 11.7%, respectively in the three cultivars). Panicles of the irrigated plants showed faster growth, the effect being more pronounced in the variety Vazhukka (115.8 cm as compared to 98.4 cm in the nonirrigated plants). Even in the variety Mysore, which normally produced shorter panicles, sprinkler irrigation increased the panicle length up to 73.8 cm whereas the nonirrigated plants produced shorter panicles (54.0 cm). Percentage of capsules which reached final maturity was significantly influenced by sprinkler irrigation in all the three varieties, Malabar, Mysore, and Vazhukka, which showed 61.3%, 55.8%, and 62.5%, respectively in the irrigated plots. The corresponding figures in the nonirrigated plots were 50.6%, 46.9%, and 52.7%, respectively for the three varieties, Malabar, Mysore, and Vazhukka.

Capsule yield almost doubled in the irrigated plots compared to the nonirrigated plots. Essential oil content of capsule was more in the irrigated plants on a dry weight basis. Mean values for the irrigated and nonirrigated plots were 10.2% and 8.2%, respectively; the highest was in the case of variety Mysore (12.2%) and the lowest in the nonirrigated plants (7.1%) in variety Malabar.

8. Drip Irrigation

In situations where water has become scarce, drip irrigation, like sprinkler irrigation has also become popular. The principle of the system is to use only enough water needed for the crop and the drip irrigation became popular in India after its great success in water-scarce Israel. It minimizes water loss by surface run off, evaporation, and percolation to deeper layers. Since the water is applied to the plant base, it is much more efficient than conventional methods of water use such as flooding. Water economy is the greatest advantage. For cardamom, application of 10–15 liter water per day is sufficient. If the cultivation is done on the contour, it is easy to practice the system. Water from small farm ponds can be drawn in this system without pumping. Drip irrigation has 80–95 efficiency (Kurup, 1978). However, the principal limitation of drip

Table XX
Effect of Sprinkler Irrigation on Cardamom Yield and the Yield Components

	Extension panicle growth (cm) to total flowers borne			Mature capsules (%)			Capsule fresh weight (g)			Capsule dry weight (g)			Essential oil content		
Cultivar	I	NI	Mean	I	NI	Mean	I	NI	Mean	I	NI	Mean	I	NI	Mean
Malabar	101.3	78.5	89.9	61.3	50.6	56.0	1465	648	1061.5	353	154	253.5	8.7	7.1	7.9
Mysore	73.8	54.0	63.9	55.7	46.9	51.3	757	421	589.0	189	107	148.0	12.2	10	11.1
Vazhukka	155.8	98.4	127.1	62.5	52.7	57.6	1919	889	1404.0	446	213	329.5	9.6	7.4	8.5
Mean	110.3	76.97	59.87			50.11			1380.33		656.0	158		10.2	8.2
"F"-test			**			*		NS	**			**			**
LSD ($p = 0.05$)			19.59			5.32			3.8			67.40			0.47
Irrigation			12.42			4.43			226			52.94			0.59
Cultivars			17.56			6.27			320			74.86			0.83

Note: I, irrigation; NI, no irrigation; NS, not significant; *, significant at 95% confidence level; **, significant at 99% confidence level.

irrigation is its initial cost for installation. It also depends on the plant spacing, as closely spaced plants, as in the State of Karnataka, would involve higher cost for installation than where spacing is wider. It would approximately cost between Rs 25,000 and 47,000 (US$600–1100) per hectare.

9. Perfospray Irrigation

This is a type of irrigation in which water is sprayed under medium pressure. In this system, aluminum or poly vinyl chloride (PVC) pipes of high density are placed 6–9 cm apart and water is pumped into this at predetermined time intervals. The setup can be shifted from one place to another and has been found suitable for cardamom (Sivanappan, 1985).

10. Contour Furrows Irrigation

Where water is on the highest point, taking advantage of the natural slope, this irrigation can be set up. Contour furrows are opened and the water is allowed to flow through them to reach the plants. If needed, small basins around the base of the plants can be made. The system requires no investment to set up. Water can also be stored in ponds or slopes along the slope and used for irrigation in summer months.

11. Time and Irrigation Frequency

In a sprinkler system, to get the effect of 25-mm rainfall, the system can be operated once in 12–15 days time interval during May–June. Soil moisture level should be above 50% of maximum water holding capacity. A stress period for about 45 days during December–January has been found to be quite beneficial. It would be ideal to commence irrigation during the first week of February and continue at an interval of 12–15 days until regular monsoon commences in the first week of June.

12. Water Harvesting

Cardamom terrain, in many instances, undulates with moderate to steep slopes. Quite a number of small and fairly big streams pass through many of these areas. Runoff from cardamom watersheds can be collected in farm ponds and check dams or underground water tapped through dug wells.

Harvested water can be stored in ponds and check dams by minimizing losses through seepage, evaporation, and recycling. Apart from improving

and stabilizing yields under rainfed cardamom cultivation, check dams, farm ponds, and dug wells reduce flood hazards and recharge ground water. Such devices in many cases will serve as percolation tanks that would substantially augment the ground water availability in the area.

F. Cardamom-Based Cropping Systems

An excellent example of forestry-cum cash crop combination is the cardamom plantation. Some of the forests are uneconomical in view of the heavy investments involved in building up adequate infrastructure for the extraction and transportation of timber. Such forests, where cardamom plantation can be established, will turn out to be economically viable. It is an environmentally harmonious system as it will not upset or adversely affect the environment or the protective quality of the forest. Cardamom is, perhaps, the only plantation crop which involves the least disturbance to the existing forest trees as against partial felling of trees to raise coffee or black pepper.

1. Sole Forest vs Cardamom Intercropped Forest: Economics and Labor Utilization

The cultivation of cardamom beneath shade trees needs to be examined to compare the benefits. An evergreen forest in the Western Ghats region managed ideally (sole forestry) can yield 10 m^2 of timber per annum per hectare. The Indian yields are much below this level. At present, the returns will be approximately 10 times more due to increase in timber cost. Moreover, clearing of forests for nonforestry purposes is not permitted now by law. Computed over a period of 20 years, the net pecuniary return from this will be Rs 700,000 (approximately US$16,300 in equivalence) and the job opportunities created will be equivalent to Rs 500,000 (US$11,600 in equivalence) according to Joseph (1978). If the area is brought under cardamom exclusively, the economic benefit, at current yield expectations and ruling price of the produce, will be to the tune of Rs 450,00,000 (approximately US$1.05 million) and the additional creation of job opportunities to the tune of Rs 80,00,000 (approximately US$1,86,000). In other words, a cardamom–forest mix could bring about substantial economic advantage. Mixed crop of cardamom–coffee and black pepper is called "multitier" cropping, as the plants attain different heights, and utilize sunlight, soil moisture and soil nutrients differentially. Different types of mixed or multitier crop combinations are discussed in a later section.

2. Mixed Cropping System

a. Nutmeg–Clove–Cardamom Combination. All the three crops, because of their different canopies, tap sunlight at different heights and also, because of their varied root systems, tap soil moisture, and soil nutrient with differing degrees of efficiency. In cardamom plantations, instead of planting other forest tree species in the vacant areas, nutmeg, or clove or both can be planted. The combination is both ecologically feasible and also economically profitable. A good example of such a combination can be seen in Burliar at an elevation of 1680 m amsl in Tamil Nadu. This plantation was started as a nutmeg garden, later clove seedlings were planted in between the nutmeg plants. Subsequently, cardamom seedlings were interplanted. Nutmeg and clove started to bear in about 6–7 years time after planting. Although both of these plants require regulated shade in the early stages of growth, clove does not require much shade once it starts to yield, and clove and nutmeg can provide shade to cardamom seedlings in their early stages of growth. Cardamom plants in this combination started to yield in about 3 years time from the date of planting and gave a yield of about 150 kg ha^{-1} of dry capsules from 600 plants. Clove, on average, yielded about 1 kg in dried form from a single plant. To meet the shade requirements of cardamom, in addition to nutmeg and clove, tall growing shade trees at regular intervals were retained in the garden. Sprinkler irrigation supplemented the shading effect.

b. Cardamom–Arecanut (Areca catechu) Combination. Arecanut is also a perennial crop like cardamom. The long prebearing age of the main crop arecanut, small income from initial harvest, the risk of pests and disease attack, remoteness from markets and inadequate transport support—all of which are features of arecanut farming in the States of Karnataka primarily—led to the evolution of introducing other crops in areca gardens (Abraham, 1956; Khader and Antony, 1968; Nagaraj, 1974). Until cocoa was introduced, cardamom was the principal crop planted in areca gardens in southern districts of Karnataka state. If one were to consider the unit value of different crop mixtures in arecanut garden, arecanut–cardamom is the best combination (Korikanthimath, 1990) at elevations between 700 and 1080 m amsl. This is because at higher elevations arecanut is not successful. Normally arecanut gardens at low-lying areas on flat land with irrigation support are most ideal for interplanting with cardamom. Investigations by Bhat and Leela (1968) and Bhat (1974) have shown that more than 80% of the arecanut plants have their root system confined to a radius of 75 cm from the base of the palms, spaced at 2.7 m × 2.7 m. Fourteen percent of the roots are at a radius of 25–50 cm and only 6% of the roots in a radius of 50–75 cm. Vertically, cardamom roots penetrate to a depth of only 40 cm. Although both

cardamom and arecanut have most of their root systems confined to the surface, there would not be much of a competition between both plants inasmuch moisture and nutrients are concerned. Muralidharan (1980) reported that 32.7–47.8% of incident light penetrates through the canopy of a 14-year old arecanut garden depending on the time of the day. Normally in a pure arecanut crop spaced at 2.7 m $\times$ 2.7 m, this quantum of light energy hits the ground and is wasted. Approximately 27% photosynthetically active radiation (PAR) passes through arecanut canopy (Balasimha, 1989). Cardamom plants interplanted in arecanut gardens can effectively utilize this energy, otherwise wasted.

In an arecanut–cardamom mixed crop field, the arecanut plant should be planted in northeast direction spaced 2.7 m between plants and rows. September–October is the ideal time to plant arecanut (Khader and Antony, 1968). Additionally, banana plants, spaced 5 m $\times$ 5 m, between arecanut plants, before arecanut plants are planted, can provide enough shade to the transplanted arecanut seedlings and would also be a good supplemental source of income to the farmer. After 7 years of planting arecanut seedlings, cardamom seedlings can be planted between the arecanut plants. In old plantations, cardamom is planted in alternate rows with a plant-to-plant spacing of 2 m. In new plantations, cardamom is planted between rows of arecanut plants. About 1250–1500 plants are accommodated in a hectare of arecanut garden.

Arecanut and cardamom share common cultural operations, such as weeding, mulching, irrigation, and so on, thereby bringing down the total cost of cultivation. It is important to apply adequate quantities of fertilizers for the supply of plant nutrients from the time the plants establish. This ensures early bearing and sustained yielding for a long time. In the south Kannada district of Karnataka State (Sirsi and adjoining areas) cardamom replanting is taken up, on a regular basis, once every 5–7 years owing to the heavy incidence of the dreaded "Katte" disease. Many planters pick two to three harvests and then replant. The "high-production technology" package for arecanut–cardamom mixture has given high yields of cardamom, as much as 625 kg of dry cardamom and 3750 kg of dry arecanut ha^{-1} year^{-1} under irrigated conditions. In nonirrigated situations, on average, the corresponding yields are 325 and 2250 kg ha^{-1} year^{-1} (Korikanthimath, 1989). Korikanthimath *et al.* (2000a) investigated the microclimatic and photosynthetic characteristics in arecanut–cardamom mixture and reported higher photosynthetic and transpiration rates and carboxylation and water use efficiency. Intercellular CO_2 concentration and stomatal conductance were higher in cardamom than in arecanut.

c. Arecanut–Tree Spices and Cardamom Combination. The above combination is seen in Koppa "taluk" (a geographical unit of land in a district known by the local language, Kannada) in the State of Karnataka. In this

combination, coconut plant acts as the first tier, followed by black pepper, which is trained on the coconut trees as second tier. Cardamom and coffee (both *Arabica* and *Robusta* varieties) are also planted in between the coconut rows. All of these crops are complementary to each other and help in maximizing income from unit area.

In Belur village of Shimoga district in Karnataka State, a "Spice Cafeteria" has been established. Cardamom was planted between arecanut plants, followed by nutmeg at a spacing of 10 m × 10 m. Clove plants were also planted in the same garden on the borders. The nutmeg trees have grown to a height of 8–10 m and their yield has been established. Clove trees yielded better when planted on the borders rather than in between the arecanut plants. On average, each nutmeg plant yields about 500–750 fruits. Clove trees yielded 750–1250 kg per tree. Around 275–400 kg ha^{-1} of dry cardamom capsules were obtained. The crop combination of arecanut as a top canopy which provides shade for nutmeg, cloves, and cardamom is found to be useful in increasing the income from unit area. Cardamom is phased out in course of time when both nutmeg and clove grow up and put forth sufficient canopy.

3. Cardamom–Coffee Mixed Cropping

Cardamom can be successfully mixed with coffee. In this combination, coffee (both *Robusta* and *Arabica* species) constitute the first tier and cardamom the second tier. Often black pepper trained on the shade trees, forms another component, and the shade tree canopy forms the top tier. Many experimental studies have gone into the merits of the coffee–cardamom combination (Table XXI).

Table XXI
Economics of Cardamom–Coffee (Arabica, Rainfed Crop) Mixed Cropping System

	Yield (dry, kg ha^{-1})		Gross income		Total expenditure	Net profit	
Year	Cardamom	Coffee	Cardamom	Coffee	Total	(Cardamom + Coffee)	
1983–1984	122.5	437.5	24,010	5486	29,496	18,750	10,746
1984–1985	300.0	175.0	54,600	2450	57,050	19,550	37,500
1985–1986	355.0	312.5	59,640	4531	64,171	21,500	42,671
Average	259.0	308.0	46,083	4156	50,239	19,933	30,305

Note: Gross income, total expenditure, and net profits are given in Rs (US$1 = approximately Rs 43).

Arabica coffee (variety S. 795) planted in 1976 at a spacing of 1.8 m × 1.8 m (triangular) was selected to study the feasibility of mixed cropping of cardamom under rainfed conditions. Every row of coffee was uprooted in 1981–1982 and subsequently cardamom was planted by providing a spacing of 5.4 m × 0.9 m (2058 plants ha^{-1}). The fertilizers, as per the recommended doses, were applied separately to cardamom. Plant protection measures and cultural operations like, weeding, mulching, shade regulation, irrigation, and so on, were followed commonly for both cardamom and coffee. An average yield of 259–308 kg ha^{-1} dry cardamom and coffee respectively was obtained during the 3 years (1983–1986). This crop combination of cardamom with arabica coffee gave a net profit of Rs 30,305 ha^{-1} (US$ approximately 700).

In another case, robusta coffee (variety Ferdinia) planted at 2.7 m × 2.7 m in 1947 was interplanted with cardamom after removal of alternate rows of coffee in 1985 to accommodate cardamom variety Malabar (Cl.37) at a spacing of 1.8 m × 1.2 m, between two rows of coffee spaced at 5.4 m × 2.7 cm. Average yield of 1907 kg ha^{-1} dry coffee (mean yield of 4 years) and 950 kg of dry cardamom capsules was obtained (Korikanthimath, 1989). This clearly demonstrates the high-production potential of cardamom–coffee combination. Srinivasan *et al.* (1992) reported that the monetary benefit can be enhanced by more than 30% by adopting cardamom–coffee planting system at a ratio of 1:1 in alternate rows either along or across the slopes. Thus the combination of coffee–cardamom offers considerable financial advantage to farmers who adopt it. Additional employment potential, efficient land and water use, effective weed control, and so on, are some of the other advantages of multistoried cropping systems over monoculture.

Inclusion of either black pepper alone as in Kerala or a combination of coffee and arecanut as in Karnataka in the multiple cropping system with cardamom is highly remunerative and can give higher benefit–cost (BC) ratio. In Karnataka State a BC ratio of 3.53 was recorded in a cardamom–coconut mixed cropping system (Korikanthimath *et al.*, 1988a). In the case of cardamom–coffee mixed cropping system, the BC was 1.94 (with single hedge system with arabica coffee) and 4.25 (with double hedge system with robusta coffee) Korikanthimath *et al.* (1989b).

4. Changes in the Rhizosphere Due to Mixed Cropping

It is but natural that when different species of plants grow in the same soil matrix, changes of different types, physical, chemical, and microbiological, do occur and from a fertility point of view, those which occur in the rhizosphere are most important. Some of these changes have been cataloged in cardamom mixed cropping systems (Korikanthimath, unpublished). On a general comparative basis, results indicated that far more microbiological

changes do occur in mixed cropping systems as compared to monocropping. In the case of cardamom–arecanut mixture, the bacterial population registered an increase of 93% in the 0- to 15-cm depth, while at lower depth (15–30 cm) the population count reduced to 29%. In the case of fungal population, the population increased with depth. It was 32% at 0- to 15-cm depth and 59% and 61% at 16- to 30-cm and 30- to 45-cm depths, respectively over the figures obtained in the case of monocropping. The actinomycetes population increased by 66% in the top 0- to 15-cm depth but thereafter decreased with depth.

When robusta coffee was mixed with cardamom, the bacterial population registered an increase of 41% at 0- to 15-cm depth, while fungal population increased by 69% in the same depth, which did not show any significant changes with increased depth. There was no effect on the actinomycetes population. In the case of arabica–cardamom–black pepper combination, the pattern in the changes of microbial or fungal population with depth was not consistent (Korikanthimath *et al.*, 2000b). However, when compared to monocropping, mixed cropping showed an increase of 71%, 98%, and 52%, respectively in the rhizosphere of arabica coffee, cardamom, and black pepper. Almost a similar increase was noted in the fungal population compared to monocropping. It must be noted that these figures refer to the total microbial, fungal, and actinomycetes count. No efforts were made in these investigations to isolate the organisms and attempt individual identification, which would have been far more informative.

5. Conclusions

The "high-production technology" for cardamom developed at the Cardamom Research Station, Appangala, Karnataka State, under the direct administrative control of the Indian Institute of Spices Research at Calicut, Kerala State, and the overall administrative control of the Indian Council of Agricultural Research, has clearly shown the benefits in farmers' fields. A combination of high-quality planting material, optimum crop and soil management techniques, and the control of pests and diseases will lead to superior yields. While production constraints do throw up challenges, constraint alleviation, especially in the area of heat and drought stress assume much importance. Cardamom must be considered not in isolation but as one important component of an entire farming system, in these tracts geared to high production and productivity.

G. Cardamom Nutrition

Traditionally, in India, cardamom is grown as an undergrowth in the dense evergreen forests of the Western Ghats of the State of Kerala without the

application of any fertilizers or providing irrigation. Subsequently, with the development of intensive agriculture, tilling the soil became a routine practice, and this led to the depletion of soil of its inherent fertility, and the felling of forest trees compounded the problem because the leaf litter was an important source of soil organic matter enriching the base soil in many ways. Heavy rainfall, which is a prime characteristic of these regions, led to surface run off, loss of fertile topsoil and plant nutrients with it. Continuous cropping in the same area also leads to the same soil debilitating effects. These ill effects necessitate the application of supplemental crop nutrients through fertilizers, primarily chemical. Among the principal plant nutrients, nitrogen, phosphorus, and potassium, cardamom is a heavy feeder of potassium. Judicious agromanagement techniques and use of high-yielding varieties are important factors influencing productivity vis-à-vis unit cost of cultivation of any crop. Among the different aspects of crop production, nutrition management is crucial because the nutrient factor decides 50% of crop productivity. And among the various factors of production, the nutrient factor is also least resilient to management. This calls for, first a clear understanding of the dynamics of cardamom nutrition, followed by precise estimations of the bioavailability of soil nutrients and schedule of dependable fertilizer practices. This section will specifically discuss the role of "The Nutrient Buffer Power Concept" in cardamom nutrition, with specific reference to potassium, since it is the most important of all the nutrients involved in cardamom nutrition.

1. The Cardamom Soils

Soils where cardamom is grown in India come under the order Alfisols, and the suborder Ustalfs, which are derived from schists, granite, and gneiss and are lateritic in nature (Sadanandan *et al.*, 1990) and these soils are formed under alternate wet and dry conditions. The soils most favorable for growth and development of cardamom are red lateritic loam with layers of organic debris present in evergreen forests, although the plant can grow on a variety of soils with only shallow zone of humus accumulation. In general, cardamom-growing soils are fairly deep with good drainage. The clay fraction is predominantly kaolinitc and hence, K fixation occurs in these soils. The cardamom-growing soils of the State of Karnataka are mostly clay loam (Kulkarni *et al.*, 1971). In Guatemala, cardamom is generally grown in rich forest soils. In the country, the crop is grown in the northern region in the recently cleared forestlands, the soils having dolomitic limestones, underlined with typical tropical clay. In the southern regions, soil is sandy clay loam with volcanic ash deposits. Soils in the south are more fertile than those of the north because of the presence of volcanic ash (George, 1990).

2. Soil Reaction

Analysis of the soil samples from several of the cardamom-growing areas shows that they are generally quite acidic, with a pH in the range of 5.0–5.5 (Zacharaiah, 1975). Nair *et al.* (1975) reported that the pH of the soils in the three important cardamom-growing districts of Kerala State, Idukki, Waynad, and Palakkad, ranged from 4.7 to 6.15, 4.75–5.2, and 5.2–5.5 respectively, and there was a slight variation in the pH with soil depth, the surface layer having higher pH than the sub surface. Ranganathan and Natesan (1985) reported that the pH of cardamom-growing areas of Tamil Nadu have pH ranging from 4.7 to 7.0 (Vadiraj *et al.*, 1998).

3. Cation Exchange Capacity

The cation exchange capacity (CEC) of the cardamom-growing soils varied from 8.6 c mol (p+) to 58.5 c mol(p+) kg^{-1}. The CEC of Coorg district soils in Karnataka is higher than that of the soils from Idukki district in Kerala State. In general, with increase in altitude, the CEC tends to increase. This is attributed to the active form of humus present in high proportion compared to the total organic matter. CEC was also found to be positively correlated to soil organic matter.

4. Organic Carbon

Organic carbon content of the soils is low at low altitude and increases as the elevation also increases. Mean organic carbon content of various cardamom-growing soils of Karnataka State was found to be 5.9% (Kulkarni *et al.*, 1971). Nair *et al.* (1978) found the organic carbon content of Kerala cardamom-growing soils to be 3.3% in Palakkad district, 3.6% in Idukki district, and 4.6% in Wayanad district. They also found the organic carbon content to decrease with depth. Srinivasan (1984) found significantly positive correlation between organic carbon and total as well as available N. The rate of organic matter decomposition in cardamom-growing soils is much lower than that of the other plantation crops growing soils, such as those where tea grows, at the same elevation because of forest tree association and consequent lower mean annual temperature (Ranganathan and Natesan, 1985).

5. Soil Phosphorus

Majority of the cardamom-growing soils are low to medium (less than 5–12.5 kg ha^{-1}) in available phosphorus. The percentage of soil samples falling

in this category is 83 for Karnataka State, 68 for Kerala State, and 63 for Tamil Nadu. This indicates that on a relative basis, soils of Karnataka State are poorer in available P compared to both Kerala and Tamil Nadu cardamom-growing soils (Anon, 1998a). Cardamom soils also contain large quantities of Fe and Al oxides and their presence leads to P fixation. The overall P fixation of cardamom-growing soils ranged from 55% at 1 h to 88% after 90 days, in the lower level of soil application at 25 kg P_2O_5 ha^{-1}, and at the higher rate of 50 kg P_2O_5 ha^{-1} application it ranged from 43% to 85% (Srinivasan and Mary, 1981). These are laboratory studies. In field conditions, these values may not apply, as the thick mulch may prevent immediate fixation of soluble P and the high organic matter content would facilitate, through their organic acid content, phosphate solubilization (Ranganathan and Natesan, 1985). Availability of P was found to decrease sharply with soil depth (Nair *et al.*, 1978; Srinivasan *et al.*, 1986).

6. Soil Potassium

In the cardamom-growing soils of India, Kerala soils are rated as high in available K (78%), while only 71% are rated as high in available K in Tamil Nadu and the least (53%) in Karnataka (Anon, 1998). This availability criterion is based on the exchangeable K and may not give an accurate picture of K availability. Srinivasan (1990) showed the K fixing capacity of cardamom-growing soils to vary from 16.9% to 32.1% for Kerala soils, 11.9–21.3% for Karnataka soils, and 19.0–23.3% for Tamil Nadu soils. K availability also decreased with soil depth (Nair *et al.*, 1978; Srinivasan *et al.*, 1986). Traditionally NH_4OAc is used as an extractant to quantify available K. Nair *et al.* (1997) have shown that K fertilizer recommendation to cardamom based on NH_4OAc extraction is not reliable and have showed that a dependable method will have to be based on the K buffer power of soils. They found, from 95 locations spread across the States of Kerala and Karnataka, that capsule yield is related to the K buffer power and not NH_4OAc extractable K, as is being routinely done and have suggested a thorough overall of K fertilizer schedule for cardamom based on the K buffer power estimation. On average, the cardamom-growing soils from the Coorg district in Karnataka State contain much less NH_4OAc extractable K than HNO_3 extractable K compared to soils from Idukki district of Kerala State, although the other soil parameters are quite comparable. Despite the lower NH_4OAc extractable K in Coorg soils the cardamom production was nearly twice as much as in Idukki soils with high HNO_3 extractable K. But the Coorg soils have a high K buffer power and since these soils maintain an optimum balance of K on cardamom plant root, are able to meet the K demands much better than the Idukki soils. These differences

reflect in cardamom yield. The authors have suggested a complete reorientation of K fertilizer strategies based on K buffer power estimation.

7. Secondary and Micronutrients

The sulfur status of cardamom-growing soils of southern India was studied by Srinivasan *et al.* (2000). Results of a total of 100 samples collected (60 from Kerala State, 28 from Karnataka State, and 12 from Tamil Nadu) showed that sulfur content ranged from traces to 36 ppm in Kerala soils, traces to 27.5 ppm in Karnataka soils, and 15–36 ppm in Tamil Nadu. If 10 ppm is considered as the critical level, 43.3% of Kerala soils and 50% of Karnataka soils could be categorized as deficient, while Tamil Nadu soils are not deficient in sulfur. Srinivasan *et al.* (1993b) who investigated the micronutrient status of cardamom-growing soils of South India indicated that available Fe ranged from 14.6 to 65.8 ppm, available Mn from 1.3 to 44.8 ppm, available Cu from 0.66 to 32.2 ppm, available Zn from 0.01 to 2.71 ppm, available B from 0.05 to 3.7 ppm, and available Mo from 0.01 to 11.1 ppm. Based on the critical levels prescribed for different micronutrients, it has been observed that 68% of the cardamom-growing areas are Zn deficient, 49% B deficient, 28% Mo deficient, and 9% Mn deficient. None of the sampled soils showed Fe or Cu deficiency. There was no deficiency of available Mn in Karnataka soils and no deficiency of available Mo in Tamil Nadu soils. Within the pH range of the soils investigated, there was a statistically significant negative correlation between soil pH and available Fe, while the relationship between available Zn and available Cu with that of soil pH was positive. Among the micronutrients investigated, only available Mn showed a statistically significant positive correlation with organic carbon content of the soil. These investigations, on the whole, indicate that among the micronutrients, Zn is turning out to be the most problematic micronutrient in the cardamom-growing soils. It is perhaps relevant to mention in this context that for precise quantification of micronutrients, especially like the problematic Zn, it would be preferable to reorient soil testing for available Zn on the basis of the "buffer power concept," as in the case of another important spice crop, namely, black pepper (Nair, 2004), which grow in similar situations like cardamom.

8. Nutrient Deficiency Symptoms

Sand culture was used to characterize nutrient deficiency symptoms in cardamom (Deshpande and Kulkarni, 1973). Following symptoms are observed (Table XXII).

Table XXII
Nutrient Deficiency Symptoms in Cardamom

Nutrient	Deficiency symptoms	Cited by
Nitrogen	First older leaves affected. Reduction in leaf size. Production of suckers is reduced and newly formed suckers dry up after some time	Deshpande and Kulkarni (1973)
Phosphorus	Symptoms appear 4–5 months later. Small purplish patches appear on leaves followed by premature leaf drop. Stunting and reduction in sucker number	Deshpande and Kulkarni (1973)
Potassium	Deficiency symptoms first appear in older leaves. Reduction of growth in shoots and roots and plants show browning of leaf tips, extending downwards later, finally the entire leaf turning dark brown in color. Further sucker production completely absent and plants died after 2 weeks from the date of first appearance of the symptoms	Deshpande and Kulkarni (1973)
Calcium	Deficiency symptoms appeared on young leaves after 75 days. Reduction in growth of shoots and roots and further growth of aerial shoot ceased. Thickening of aerial stem showing bulb-like growth. Scattered yellow spots on leaves and margins which turn brown with golden-yellow band underneath	Deshpande and Kulkarni (1973)
Magnesium	Reduction in internodal length and plant appears broom-like. Twisting of top leaves, leaf tip drying. Later the whole leaf becomes pale yellow, mid rib turning green. White papery spots on leaf lamina, which is the most commonly observed symptom in the nursery. Inhibition of sucker production	Deshpande and Kulkarni (1973)
Sulfur	First appear on young leaves and growing leaf becomes whitish in color, followed by death of leaves starting from the margins	Deshpande and Kulkarni (1973)
Zinc	Poor plant growth, curled leaves, interveinal chlorosis	Anon (1979)
Boron	Reduction in leaf size and cracking of leaf lamina	

9. Shade Trees and Soil Fertility

Cardamom is cultivated under shade trees and the soils in general have high fertility status due to the addition of leaf litter and recycling of plant nutrients (Zachariah, 1978). Nair *et al.* (1980) observed that shade trees bring to the soil surface the nutrients they take up from the lower layers of soil. Even though on average about 5.5 t ha^{-1} of organic material as leaf litter, weeds, and pruned plant parts are recycled in a cardamom plantation in a year, the nutrients are mainly in the organic form and are available to the crop only by the process of mineralization. As the rate of mineralization is always low, the nutrients that become available to the crop will be able to sustain only average growth with average production (Srinivasan *et al.*, 1993a).

10. Plant Nutrient Composition and Uptake

a. Tissue Concentration. A number of investigators (Kulkarni *et al.*, 1971; Pattanshetty, 1980; Raghothama, 1979; Ratnavele, 1968; Srivastava *et al.*, 1968; Sulikeri, 1986; Venkatesh, 1980) have documented the tissue concentration of the entire cardamom plant and also after partitioning it into various parts. Between the second and fifth leaves, the P and K contents were more in the leaf tip of the second leaf, and all the other leaves contained lesser amounts, whereas in the case of Ca, the least content was found in the second leaf and all the others contained more (Ratnavele, 1968). The aerial stem contained more K than the leaves (Ratnavele, 1968). Kulkarni *et al.* (1971) reported that as the plant aged, while N, P, and Ca contents in leaves increased, there was a general reduction in Mg and K contents. At bearing stage, while the major nutrients decreased in the leaf tissue, an increase was observed in the case of Ca and Mg. A similar trend was observed in aerial stem as the plant aged. Rhizomes contain lower levels of major nutrients than roots, whereas roots contain more of secondary nutrients. In general, N content was the maximum in leaves, followed by shoots, rhizomes, and roots (Pattanshetty, 1980; Raghothama, 1979; Venkatesh, 1980;). K content was found to be the highest in shoots followed by rhizomes and leaves. No definitive pattern was observed with regard to P in these investigations. Sulikeri (1986) reported the highest N content in leaves, followed by rhizomes, shoots, and roots during prebearing stage. By harvest time, the nutrient content increased in all plant parts except leaves where it was found to decrease. P content did not vary much in different plant parts during prebearing period, whereas at harvest, capsules contained more of P than any other plant part. During prebearing stage, the maximum of K was found in rhizomes, followed by shoots, leaves, and roots. At harvest also, the same trend was noticed except the fact that capsules and panicles contained more K than leaves and roots. K content at harvest decreased in all plant parts compared to

the prebearing stage except in rhizome where its concentration increased. Ca was highest in leaves at prebearing stage and at harvest stage capsules recorded the maximum content, while Mg content was maximum in leaves and minimum in shoots both at prebearing stage and at harvest.

All of the above clearly show that individual nutrients have specific pattern of accumulation in the cardamom plant parts coinciding with different growth stages and no two nutrients follow similar pattern.

b. Nutrient Uptake. For the production of a kilogram of cardamom capsules 0.122 kg of N, 0.014 kg of P, and 0.2 kg of K are exported by the plant from soil. For the plant, as a whole, N, P, K, Ca, and Mg ratio worked out to be 6:1:12:3:0.8 (Kulkarni *et al.*, 1971). A similar ratio was reported by Venkatesh (1980) also. Maximum uptake of N (53%) and Ca (47.5%) was shown by leaves followed by shoots, whereas in the case of P, K, and Mg a reverse order was observed. Uptake by rhizomes and roots followed in the descending order (Pattanshetty, 1980). Among the major nutrients, uptake of N was more than that of P and K during the prebearing stage than at harvest. At harvest there was considerable decrease in N uptake by leaves, while the rhizomes and shoots showed an uptrend. In the case of P and K, the maximum uptake was at harvest by shoots, and there was reduction in N uptake by leaves. Rhizomes occupied the second position in uptake of K at harvest indicating the importance of K in cardamom production.

Among secondary nutrients, the maximum Ca uptake was by shoot at prebearing and harvest stages, while in the case of Mg, it was the leaf. Ca uptake by shoot was more at harvest than that at prebearing stage. In the case of Mg a reverse trend was observed (Sulikeri, 1986).

From the above data, it can be concluded that of all the nutrients, K is the most important for good cardamom production. In terms of importance, the nutrients can be ordered as follows: K, N, and P. Soils which rate high for K availability, as in the case of soils from the State of Karnataka, produce good cardamom yields (Kulkarni *et al.*, 1971). Cardamom is extensively grown in the Western Ghats, Wayanad, and Idukki districts of Kerala State, and where the soils have been rated high for K availability, good cardamom yields followed.

H. Fertilizer Requirements

1. Scheduling Fertilizer Application

Up to the mid-1950s, cardamom grew in the forest ecosystem and not enough attention was given to scientific fertilizer scheduling. Manuring was confined just to organic manures, if at all any was applied. As the crop gained increasing national and international importance, as an important cash

earning spice crop, farmers realized the benefits of fertilizer application and the resultant increase in crop yield. A dose of N, P_2O_5, and K_2O in the ratio of 45:45:45 kg ha^{-1} for Kerala soils, 67:34:100 kg ha^{-1} for Karnataka soils where half of the N quantity applied was in organic form and 45:34:45 kg ha^{-1} for Tamil Nadu soils was suggested by de Geus (1973). Zachariah (1978), on the other hand, suggested a maintenance dose of N, P_2O_5, and K_2O in the ratio of 30:60:30. Based on further investigations, to obtain a total yield of 100 kg ha^{-1} of dry capsules, the dose of fertilizers suggested was in the ratio of 75:75:150 kg ha^{-1}. If the target yield was more, the fertilizer dose has to be proportionately increased. An additional dose of 0.65 kg N and P_2O_5 and 1.30 kg K_2O ha^{-1} was suggested for an increase in yield of every 2.5 kg of dry capsules over normal yield (Anon, 1976; Kologi, 1977).

Results of investigations (Srinivasan *et al.*, 1998) indicated that significant yield increase and economy of fertilizer use can be brought about through a combination of soil and foliar applications. In Karnataka, N, P_2O_5, and K_2O at the rate of 37.5:37.5:75 kg ha^{-1} through soil application supplemented with a foliar application of 2.5% urea + 0.75% single super phosphate + 1.0% MOP of potash gave 64 kg ha^{-1} more of capsule yield compared to no fertilizer application. In Tamil Nadu with a soil application of N, P_2O_5, and K_2O at the rate of 20:20:40 kg ha^{-1} supplemented with a 3% urea + 1% of single super phosphate + 2% of MOP gave a yield increase of 43 kg ha^{-1}. In irrigated plantations, the general fertilizer recommendation is to apply N, P_2O_5, and K_2O at the rate of 125:125:250 kg ha^{-1} to soil in three splits (Anon, 1997). Kumar *et al.* (2000) also suggested application of N, P_2O_5, and K_2O at the rate of 75:75:150 kg ha^{-1} in Karnataka soils. Urea was to be a better source of N compared to ammonium sulfate (Deshpande *et al.*, 1971). For cardamom-growing soils, which are rich in organic matter and acidic in reaction, "Mussorirockphosphate" (a natural rockphosphate mined in North India) was found to be the ideal source of P (Nair and Zachariah, 1975). When plant density increased to 5000 plants ha^{-1} under trench system of planting, fertilizer application has to be at a higher rate, 120:120:240 kg ha^{-1} of N, P_2O_5, and K_2O (Korikanthimath, 1986). This combination was subsequently revised as 150:75:300 kg N, P_2O_5, and K_2O ha^{-1} (Korikanthimath *et al.*, 1998a). In low-rainfall area of Lower Pulney tracts of Tamil Nadu, a fertilizer dose of 40:80:40 kg ha^{-1} of N, P_2O_5, and K_2O ha^{-1} is recommended (Natarajan and Srinivasan, 1989).

Srinivasan and Bidappa (1990) investigated nutrient combinations based on P and K adsorption isotherms. The total phosphorus requirement (TPR) was calculated as follows: TPR (kg ha^{-1}) = $(60 - x) \times 3.24$, where 60 = the desired soil fertility level for P, x = the soil test value for P and 3.24 is a constant derived by taking into account soil bulk density, weight of soil per hectare. The total potassium requirement per kilogram = $(300 - x) \times 2.64$, where 300 = the desired soil fertility level for K, x = the soil test value for K

and 2.64 is the constant derived as explained previously. The recommended rates derived maintain soil P and K levels at 60 and 300 kg ha^{-1} as these levels are considered optimum for cardamom. Ranganathan and Natesan (1985) reported beneficial application of zinc sulfate to nursery plants by incorporating the salt with the fertilizer mixture.

Sivadasan *et al.* (1991) found that application of 500 ppm zinc sulfate as foliar spray enhanced growth, yield as well as quality of the produce. Deshpande *et al.* (1971) found the beneficial effect of liming cardamom soils in correcting soil acidity and enhancing the rate of nitrification resulting in better plant growth. However, subsequent observations (Anon, 1997; Nair *et al.*, 1998) indicated that liming is not required as a routine practice in cardamom plantations. Table XIII shows the schedule of fertilizer application.

When application of fertilizer is routed through soil, it would be necessary to apply one-third of the recommended dose (75:75:150 kg ha^{-1} and 125:125:250 kg ha^{-1} of NPK for rainfed and irrigated conditions, respectively) during the first year of plant growth both under rainfed and irrigated conditions. During the second year of plant growth, the dose may be increased, to one half of the recommended dose and fertilizer at full dose many be applied from third year onwards (Anon, 1993).

All of the above fertilizer recommendations are based on the conventional/routine analytical techniques and not on the basis of advances in soil testing and fertilizer recommendations based on "The Nutrient Buffer Power Concept" developed by Nair (1996). Application of this concept in the case of K requirement of cardamom led to dependable yield targeting (Nair *et al.*, 1997). Nair (2002) has suggested a thorough reorientation of soil testing based on the "buffer power concept" for precise fertilizer recommendations in many crops, including cardamom.

Organic manures are considered essential for improving physical characteristics of soil, apart from their fertility enriching qualities, and these manures are indispensable in cardamom cultivation whether chemical fertilizers are applied or not. Application of organic manures, such as neem cake (1–2 kg per plant) or farm yard manure or cattle dung compost, at the rate of 5 kg per plant may be made once in a year in May–June along with "Mussoriephosphate" and MOP (Anon, 1997). Thimmarayappa *et al.* (2000) suggested an integrated nutrient management approach to meet the 25% requirement of N through farmyard manure and the remaining 75% through inorganic sources for sustained cardamom production over a period of time.

2. Diagnostic Recommendation Integration System

The application of the Diagnostic Recommendation Integration System (DRIS) originally detailed by de Gues (1973) has been tested in cardamom by

Sadannandan *et al.* (2000). They analyzed different nutrients in the youngest mature leaf (fifth pair) from the terminal emerged panicle-bearing tillers along with crop yield and tested the efficacy of the DRIS system. Leaf nutrient composition was categorized as deficient, low, optimum, and high. As per the norms developed, leaf with 1.26–2.81% N, 0.1–0.2% P, 1.1–3.4% K, 0.51–1.38% Ca, 0.18–0.31% Mg, 135–370 ppm Fe, 261–480 ppm Mn, 20–45 ppm Zn, 10–46 ppm Cu, and 0.28–0.84% Mo is considered optimum for producing cardamom yield ranging from 131 to 625 kg ha^{-1}. From this investigation it was observed that to obtain a high yield of 378 kg ha^{-1} the indicator leaf should have a mean N, P, K, Ca, and Mg level of 2.04%, 0.15%, 2.25%, 0.95%, and 0.25%, respectively. The optimum level of micronutrients for realizing a high-yield level is 253 ppm Fe, 371 ppm Mn, 33 ppm Zn, 28 ppm Cu, and 0.56 ppm Mo. Their principal observation was, among all the nutrients investigated, K requirement was highest for attaining maximum yield level and it should be 2.25% in the leaf. The descriptive diagnostic chart depicting all the nutrients investigated is shown in Fig. 2.

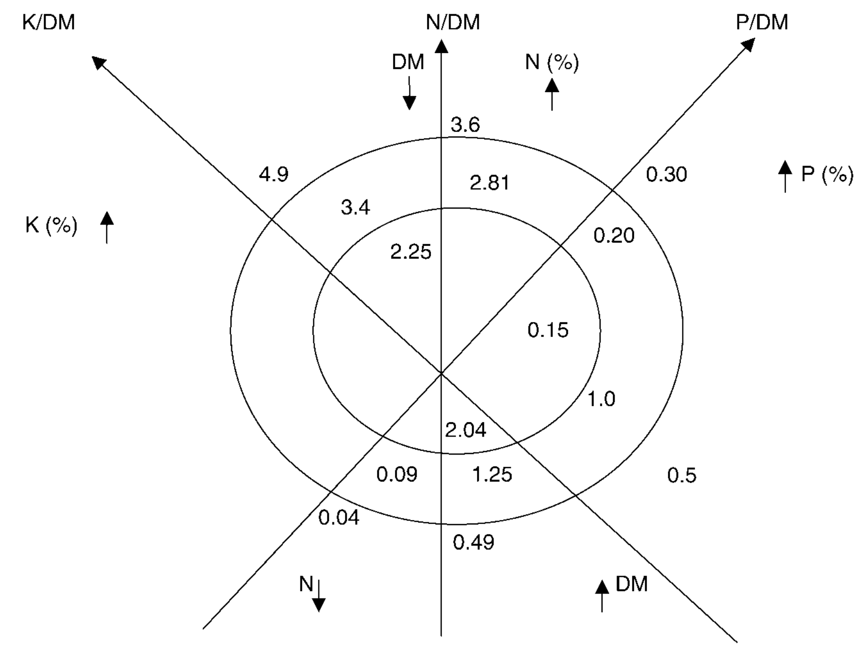


Figure 2 Foliar diagnostic norms for optimizing cardamom production (DRIS norms chart).

3. Method and Time of Fertilizer Application

To decide the right time and method of fertilizer application for cardamom, the root spread should be taken into consideration. Lateral spread of roots of a full bearing 8-year-old plant was found to have 80% of its roots in a zone of 25-cm radius, 14% in a zone of 25- to 50-cm radius, and only 6% in a zone of radius 50–75 cm. Vertically cardamom roots penetrate only up to 40-cm deep (Khader and Sayed, 1977). Further studies conducted at the Indian Cardamom Research Institute (Nair, 1988) also showed that roots of cardamom are confined only to a shallow depth. Nearly 70% of roots were seen at the top 5-cm depth. Horizontally, only 10% of the roots forage an area 120 cm away from the clump. Therefore, for the maximum efficiency of applied fertilizers it would be necessary to apply them at a radius of 50 cm. Since cardamom is a surface feeder, deep placement of fertilizers is not advisable, as for instance, in the case of cotton. Before application of fertilizers, if the panicles spread on the ground, they are to be kept coiled encircling the base of the plant and the mulch should be removed. Fertilizers may be applied around the plant base in a circular band of 15-cm width, leaving about 30 cm from the plant base and incorporated in the soil by using a hand fork. Mulching should be followed immediately after incorporating fertilizers. Panicles may then be released and spread on the ground for the Malabar types to facilitate honeybee movement for better pollination and capsule set.

Cardamom growth is influenced by seasonal conditions, especially rainfall pattern. From the bases of tillers vegetative buds emerge throughput the year. However, majority of the vegetative buds are produced after the rains (Sudharshan *et al.*, 1988). It was observed that the linear growth of tillers increases with the onset of southwest monsoon and the growth rate slows down with the cessation of monsoon. Peak flowering and fruit set periods coincide, and nearly 70–90% of flower production occurs between May–August. Hence, for the efficient utilization of fertilizers, the time of their application is crucial. Application of fertilizers in the month of May and later in September is found to be most beneficial (Pattanshetty and Nusrath, 1973). However, under irrigated conditions, tiller and panicle initiation are continuous processes and split application of fertilizers is preferable.

Since cardamom grows in forest situations with shade trees all around, complete utilization of fertilizers will not take place as there would be competition from the roots of other trees/herbs and shrubs for both moisture and nutrients. Hence, a combination of soil and foliar application is preferable than resorting exclusively to soil application of fertilizers. Soil application in two rounds, first during May–June and later August–September and subsequent supplemental foliar applications in September, November, and January are recommended (Srinivasan *et al.*, 1998). George (1990) reported

that in Guatemala, almost all growers fertilize cardamom unlike in India. Different fertilizer mixtures are available in the country. One such is an NPK mixture in the ratio of 15:15:15, which is marketed under the trade name "Barco Vikingo." Another mixture which contains Ca and Mg in addition to NPK is a mixture of NPKCa and Mg in the ratio of 18:6:12:4:0.2 with the brand name "Agrovet S.A." Fertilizer application starts from the second year after planting when just 2 oz of the mixture is added per plant. This is gradually increased to 3 oz in the third year and to 4 oz from the fourth year onwards. Some cardamom planters add an extra dose of 1 oz of urea to each plant over the quantity of mixture applied. The recommended dose is applied 2–4 times in a year (George, 1990). In India, when cardamom is cultivated under controlled artificial shade, a fertilizer dose of NPK in the ratio of 100:25:100 kg ha^{-1} is recommended to be applied (Korkanthimath *et al*., 1988b).

V. THE ROLE OF "THE NUTRIENT BUFFER POWER CONCEPT" IN CARDAMOM NUTRITION

Historically, soil testing has been used to quantify availability of essential plant nutrients to field grown crops. However, contemporary soil tests are based on philosophies and procedures developed several decades ago without significant changes in their general approach. For a soil test to be accurate, one needs to clearly understand the physicochemicophysiologic processes at the soil–root interface, and an understanding of the soils and plant root systems as polycationic systems is essential. It is this knowledge that leads to sound prescriptive soil-management practices in nutrient bioavailability vis-à-vis fertilizer application, because of all the factors that govern sustainability of crop production, the nutrient factor is the most important and, at the same time, least resilient to management. This section will focus on the buffering of nutrients, with specific reference to K, the most important major plant nutrient in cardamom nutrition, and discuss field experimental results in cardamom management.

A. The "Buffer Power" and Effect on Nutrient Availability

1. Basic Concepts

In any nutrient management approach that is sound and reproducible, one must start with a basic understanding of the chemical environment of plant roots. When we consider this, the first term that we come across is the

"soil solution," because the plant root is bathed in it and is most affected by its chemical properties. The Soil Science Society of America (1965) defines soil solution as "the aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials." Adams (1974) has given a simple definition: "The soil solution is the aqueous component of a soil at field-moisture contents." Perhaps it is important to emphasize here that much of contemporary soil testing has considered a soil extract as synonymous with the soil solution. Since soil extraction is supposed to simulate plant root extraction, it is pertinent to consider the chemical environment of the root, although briefly, from this angle. It is worth noting that the chemical environment of roots in natural soil systems is so obviously complex that both soil scientists and plant physiologists have been unable to provide a precise definition. If this complex chemical system is to be accurately quantified, thermodynamic principles will need to be used to evaluate experimental data. Even then, the limitations are obvious, as in the case of K where the thermodynamic investigations are quite often inapplicable under field conditions. This is because, although a quasi-equilibrium in K exchange can be achieved in the laboratory, these conditions are seldom, if ever, attained under field conditions (Sparks, 1987). Agricultural soils are, for the most part, in a state of disequilibrium owing to both fertilizer input and nutrient uptake by plant root. It thus appears that a universal and accurate definition of a root's chemical environment awaits the proper application of thermodynamics for the root's ambient solution (Adams, 1974) or even kinetics, as in the case of K (Sparks, 1987), where thermodynamics has been found inadequate.

Soil extractions with different extractants provide a second approach in defining the root's chemical environment. This approach has been particularly successful in understanding cases like P insolubility, soil acidity, and K fixation. However, this approach also fails to define precisely the root's chemical environment. Although this approach also suffers from deficiencies, such as the extractants removing arbitrary and undetermined amounts of solid-phase electrolytes and ions (or the extractants causing precipitation of salts or ions from the soil solution), and the soil–plant interrelationship defined in terms of the solid phase component of the soil, even though the solid phase is essentially inert except as it maintains thermodynamic equilibria with the solution phase (Adams 1974), the latter part could be researched more to understand how the solid phase–solution phase equilibria can be interpreted to give a newer meaning to quantifying nutrient availability. It is in this context that the role of the plant nutrients' "buffer power" assumes crucial importance.

The close, almost linear, relationship in a low-concentration range of <0.5 mM for NO_3^-–N, NH_4^-–N, K^+, $H_2PO_4^{2-}$, and $H_2PO_4^{2-}$, which has

been established by numerous solution culture experiments, can be quantitatively described by the equation

$$U = 2\pi r \alpha C_r, \quad (1)$$

where U = uptake of a 1-m root segment, "r" = root radius, C_r = concentration of the ion at the root surface, and α = root absorbing power (Mengel, 1985). The metabolic rate of the root determines its absorbing power. A high root absorbing power would imply that a relatively high proportion of nutrient ions coming in contact with the root surface is absorbed and vice versa. The nutrient ion concentration at the root surface (C_r) depends on α since a high root absorbing power tends to decrease C_r; it also depends on the rate of movement from bulk soil toward the root (Mengel, 1985). Diffusion and/or mass flow controls this movement but it is now established that nearly 95% of this movement for nutrients such as P, K, and Zn (among heavy metals) and, possibly NH_4^+, is by way of diffusion. When root uptake of ion species is less than its movement toward it, accumulation of the ion species on the root surface is bound to occur, as has been shown to be the case with Ca^{2+} where mass flow contributes to this accumulation (Barber, 1974). The diffusive path for ions, such as P and K, which plant roots take up at high rates but which are in low concentration in the soil solution near the root, is the concentration gradient. In a sense, the effective diffusion coefficient which quantifies the diffusive path and the buffer power are analogous because the diffusive flux across the root surface is integrally related to the nutrient buffer power. This has been shown to be true in the case of P where a highly significant positive correlation between the two was found to exist in 33 soil samples obtained from experimental sites in the United States and Canada (Kovar and Barber, 1988). However, in a routine laboratory setup, it is far easier to measure the buffer power than the effective diffusion coefficient and this chapter will further focus on the question of how buffer power can be quantified without recourse to cumbersome analytical techniques and how its integration into routine soil test data will considerably improve predictability of nutrient up take.

B. Measuring the Nutrient Buffer Power and Its Importance in Affecting Nutrient Concentrations on Root Surfaces

The ability to predict the mobility of dissolved chemicals, such as fertilizers, in the soil is of considerable value in managing fertilizer applications. Soil testing, in its essence, aims to achieve this. While modeling transport and retention of ion from thermodynamic (Selim, 1992), kinetic (Sparks, 1989), and mechanistic (Barber, 1984) angles could be informative, the importance of translating this information in to practically feasible procedures in crop

production calls for an understanding not only of the basic concepts but of their intelligent application as well. In a dynamic state of plant growth, the concentration of any nutrient on the root surface is nearly impossible to measure since both the nutrient in the plant tissue and the root absorbing power, which directly affects it, change quickly due to root metabolic processes. The inability of even mechanical mathematical models to accurately predict nutrient influx rates has been highlighted (Lu and Miller, 1994). Hence, if an effective soil testing procedure is to be devised for a nutrient, which is an alternative to defining the plant root's chemical environment, one must resolve the problem of quantifying the nutrient concentration on the root surface indirectly, even if it is impossible to resolve it directly, for the reasons mentioned previously.

Using Fick's first law,

$$F = -D\left(\frac{\mathrm{d}C}{\mathrm{d}x}\right), \tag{2}$$

where F = the flux, $\mathrm{d}C/\mathrm{d}x$ = concentration gradient across a particular section, and D = the diffusion coefficient, Nye (1972) has suggested that the formula can be applied to both ions and molecules. The negative sign for D implies net movement from high to low concentration. Although for molecules in simple systems like dilute solutions D may be nearly constant over a range concentrations, for ions in complex systems like soils and clays D will usually depend on the concentration of the ion and on that of other ions as well (Nye, 1979). Nye (1979) has further suggested that although Fick's first law may be derived from thermodynamic principles in ideal systems, in a complex medium, such as the soil, the above-mentioned quotation may be regarded as giving an operational definition of the diffusion coefficient. Thus, Nye (1979) defines the diffusion coefficient as

$$D = D_1 \theta f_1 \left(\frac{\mathrm{d}C_1}{\mathrm{d}C}\right) + D_\mathrm{E}, \tag{3}$$

where D_1 = diffusion coefficient of the solute in free solution, θ = the fraction of the soil volume occupied by solution and gives the cross section for diffusion, f_1 = an impedance factor, C_1 = concentration of solute in the soil solution, D_E = an excess term which is zero when the ions or molecules on the solid have no surface mobility, but represents their extra contribution to the diffusion coefficient when they are mobile. D_E can generally be neglected since only in rare instances will it play any role in diffusion of plant nutrient ions in soil (Mengel, 1985). From the point of view of nutrient availability, $\mathrm{d}C_1/\mathrm{d}C$, which represents the concentration gradient, assumes crucial importance, as we shall see later.

The term $\mathrm{d}C_1/\mathrm{d}C$, where C_1 = concentration of the nutrient ion in the soil solution and C = concentration of the same ion species in the entire soil

mass, assumes considerable significance in lending a practical meaning to nutrient availability. If we ascribe the term "capacity" or "quantity" to C and "intensity" to C_1, we have in this term an integral relationship between two parameters that may crucially affect nutrient availability. Since the concentration gradient of the depletion profile of the nutrient in the zone of nutrient uptake depends on the concentration of the ion species in the entire soil mass (represented by "capacity" or "quantity") in relation to the rate at which this is lowered on the plant root surface by uptake (represented by "intensity"), it could be argued that a quantitative relationship between the two should represent the rate at which nutrient depletion and/or replenishment in the rooting zone should occur (Nair, 1984a). This relationship has been functionally quantified by Nair and Mengel (1984) for P in eight widely differing central European soils (Table II) and the term dC_1/dC has been referred to as the "nutrient buffer power." Nair and Mengel (1984) used electroultra filtration to quantify C_1 while using an incubation and extraction technique to quantify C. For P, C was found to closely approximate isotopically exchangeable P (Keerthisinghe and Mengel, 1979), but in the experiments conducted by Nair and Mengel (1984), it was estimated by extraction of incubated soil with an extractant which was a mixture consisting of 0.1 M Ca lactate + 0.1 M Ca acetate + 0.3 M acetic acid at pH 4.1. The extractant exchanges adsorbed phosphate and dissolves Ca phosphates except apatites; the method known as the "CAL-method," developed by Schuller (1969), is now widely used in central Europe. In the case of K^+ and NH_4 –N, C denotes the concentration of exchangeable, and to some extent nonexchangeable, fractions (Mengel, 1985). Since low concentrations in the range of 2.0 μM may be attained on the root surface for both P and K (Claassen and Barber, 1976; Claassen *et al.*, 1981; Hendriks *et al.*, 1981), Nair and Mengel (1984) had to use electroultrafiltration (EUF) to quantify C_1. Thus, the nutrient depletion around the roots which is caused by the diffusive flux of the nutrients toward the root surface is related to both the quantity and the intensity parameters, and a quantifiable relationship between both represents the buffer power specific to the nutrient and the soil. A growing root will at first encounter a relatively high concentration of P which is in the range of the concentration of the bulk soil solution (Nair and Mengel, 1984). As uptake continues, depletion will occur at the root surface. This depletion profile gets flatter with enhanced nutrient uptake (Claassen *et al.*, 1981; Hendriks *et al.*, 1981; Lewis and Quirk, 1967). But it is the capacity of the soil to replenish this depletion, which ensures a supply of nutrient ions to the plant root without greatly depressing its average concentration on the root surface. It is the nutrient's buffer power that decides these depletion and/or replenishment rates. A soil with a high P buffer power implies that the P absorbed from the soil solution is rapidly replenished. In such a case, P concentration at the root surface decreases only slowly and

this means P concentration at the root surface remains relatively high. In soils with a low P buffer power, the reverse is true, and P concentration at the root surface is rapidly diminished and remains relatively low. This has been proved experimentally for P (Nair, 1992; Nair and Mengel, 1984; Table XXIII). This phenomenon holds true for Zn^{2+} (Nair, 1984a,b), K, and NH_4^+–N as well Mengel (1985).

C. Quantifying the Buffer Power of Soils and Testing Its Effect on Potassium Availability

The dynamics of K availability follows the same pattern as that of P, especially in the range of low concentrations. Beckett (1971) has used the activity ratio for K^+ and Ca^{2+} to determine K availability. Since interlayer K would play an important role in K availability, it would be more logical to consider K buffer power in determining K availability. Routinely it is the ammonium acetate extractant that is widely used to characterize K availability. The reason that this may not be suitable to characterize exchangeable K is that in the routine extraction, only the top layer is extracted, while interlayer K from which deep-rooted plants can feed is ignored (Nair *et al.*, 1997). There is extensive evidence to substantiate this Nair (1985). The importance of interlayer K in the nutrition of deep rooted and perennial crops, such as cardamom, the world's most valuable spice crop next to black pepper, is highlighted in this section.

D. The Importance of K Buffer Power Determination in Predicting K Availability to Perennial Crops

As in the case of P, the K buffer power assumes great importance in predicting K availability, especially with regard to deep-rooted and perennial crops. K availability has been studied with reference to the exchangeable K. However, with perennial and deep-rooted crops, nonexchangeable and interlayer K play a crucial role in K availability. Three soil parameters that control the rate of K supply to plant roots which have been used for predicting K absorption by plants are K intensity in the soil solution, the K buffer power, and the effective diffusion coefficient (Beckett, 1971; Claassen *et al.*, 1986; Mengel and Kirby, 1980). K buffer power can be directly obtained from the K quantity–intensity relationship. The effective diffusion coefficient depends on, among other factors, the buffer power (Nye, 1972). Plants feed not only from exchangeable K^+, but also from non-exchangeable K^+, which mainly consists of K^+ trapped in the interlayers

Table XXIII
Fertilizer Schedule in Cardamom and Comparison of P Buffer Power of Central European Soils

I. Fertilizer schedule in cardamom[a]

Region	Soil application	Soil + Foliar application	Time of application	
			Soil	Foliar
Karnataka	NPK 75:75 (150 kg ha^{-1})	NPK 37.5:37.5:75 (kg ha^{-1}) Urea (2.5%) Single super phosphate (0.75%) Muriate of potash (1.0%)	May–June August–September	September November January
Kerala	NPK 75:75 (150 kg ha^{-1})	NPK 37.5:37.5:75 (kg ha^{-1}) Urea (2.5%) Single super phosphate (0.75%) Muriate of potash (1.0%)	May–June August–September	September November January
Tamil Nadu	NPK 40:80:40 (kg ha^{-1})	NPK 20:40:20 (kg ha^{-1}) Urea (3%) Single super phosphate (1.0%) Muriate of potash (2%)	September November	June, August, November–December

II. Comparison of P buffer power of eight widely differing central European soils (determined by two different techniques)[b]

Soil	Regression functions (1)	Regression functions (2)	"r" Values (1)	"r" Values (2)
Benzheimer Hof	$Y = 18.8x + 7.94$	$Y = 0.23x + 8.98$	0.912	0.995
Hungen	$Y = 38.2x - 1.03$	$Y = 4.32 + 0.25x$	0.967	0.997
Oldenburg B6	$Y = 49.8x + 0.52$	$Y = 0.72 + 0.26x$	0.994	0.999
Wolfersheim	$Y = 70.3x + 0.03$	$Y = 0.11 + 0.27x$	0.998	0.983
Obertshausen	$Y = 70.5x + 2.66$	$Y = 2.89 + 0.30x$	0.966	0.998
Oldenburg B3	$Y = 73.6x + 2.07$	$Y = 0.61 + 0.31x$	0.994	0.997
Klein-Linden	$Y = 75.0x + 0.38$	$Y = 1.81 + 0.32x$	0.999	0.991
Gruningen	$Y = 75.4x + 0.89$	$Y = 3.62 + 0.36x$	1.000	0.996

[a] Instead of straight fertilizers, 2% each of diammonium phosphate (DAP) and muriate of potash (MOP) can be used.

[b] The b values in the regression functions represent the P buffer power of each soil. In regression function (1) (after Nair and Mengel, 1984) Y = CAL-P (Schüller's method) and in regression function (2) (after Nair, 1992) Y = the author's method. x in both refers to electroultrafiltrable P. Note the very high r values in all the cases. The soils are arranged in their sequential increase in P buffer power.

of nonexpanded 2:1 clay minerals (Hoagland and Martin, 1933; Schachtschabel, 1937).

Exchangeable K^+ comprises that which can be exchanged with NH_4 ion, and is primarily planar K^+, the interlayer K^+ of expanded 2:1 clay minerals and some of the K^+ at the interlayer edges of nonexpanded 2:1 clay minerals. Interlayer K^+ of nonexpanded clay minerals, such as illites and interlayer, and lattice K^+ micas (present in feldspars) constitute the nonexchangeable K^+. The interlayer K^+ is of particular importance in the nutrition of deep-rooted and perennial crops, such as cardamom, as demonstrated by Nair *et al.* (1997), and also for annual crops such as rye grass (*Lolium perenne*. cv. Taptoe) (and Uhlenbecker, 1993).

In most of the test for K^+ availability, nonexchangeable K is not considered. For cereals, such as wheat (*Triticum aestivum*), 80% of the K^+ extracted by the crop came from non exchangeable K pool. This is one of the most important reasons for the poor soil test crop response relationship with regard to K fertilizer application based on such tests (Kuhlmann and Wehrmann, 1984). The contribution of nonexchangeable K to plant availability was assessed by 1 M HCl extraction by Schachtschabel (1961), similar to the 1 M HNO_3 extraction proposed by Pratt (1985) and McLean and Watson (1985). However, the efficiency of IM HCL extraction to quantify plant available K from the nonexchangeable pool has been disputed (Boguslawski and Lach, 1971; Grimme, 1974; Kuhlmann and Wehrmann, 1984). Soils containing primarily 2:1 clay minerals, such as vermiculite and illite, have interlayer K in excess of crop requirements. However, the availability of interlayer K of nonexpanded minerals is independent of the quantity of interlayer K as such, but dependent on its release rate depending on the type of K^+ bearing minerals (Sparks, 1987). Release of K from interlayer positions is an exchange and diffusion process (von Reichenbach, 1972). While exchange depends on the cation species and their concentration near the surface of the mineral, diffusion depends largely on the expansion of the mineral and therefore on soil moisture. Net release of K will only occur if the K concentration of the adjacent solution is low (, 1985). Martin and Sparks (1983), while studying the release of nonexchangeable K^+ from sandy loam and loamy sand extracted with a H^+ charged ion exchanger resin, found large release of K^+ with a K^+ concentration of about 1–2 μmole in the contact solution. This concentration may approximate the rhizosphere concentration level. Under submerged conditions as in rice, there can be a depletion zone for K in the rhizosphere (Xu and Liu, 1983). Plant roots act as a sink for K and maintain the K solution concentration at low levels (Kuchenbuch and Jungk, 1984). This would cause further release of interlayer K (1985). These considerations point to the important fact that a precise quantification of K availability, where nonchangeable interlayer K

is concerned, hinges primarily on release rate, which the K buffer power attempts to quantify, as we shall see in the following discussion.

Nair *et al.* (1997) selected cardamom to demonstrate the importance of nonexchangeable and interlayer K on K availability vis-à-vis the K buffer power. The K buffer power curves were constructed by a two-step extraction in which 1N HNO_3 was used to determine K quantity (Wood and De Turk, 1941) and 1N NH_4OAc was used to determine K intensity. The NH_4OAc extractant is universally used to determine exchangeable K. The contribution of nonexchangeable K to plant availability has been assessed both by extraction with 1 M HCl (Schachtschabel, 1961) and 1 M HNO_3 (McLean and Watson, 1985; Pratt, 1965). Nair *et al.* (1997) regressed 1N HNO_3 extractable K (y) over 1N NH_4OAc extractable K (x) to obtain the K buffer power (Table XXIV).

Data in Table XXIV clearly indicate that the Coorg soils, which had a much higher K buffer power, produced cardamom yield which was twice that obtained in the Idukki soils. The higher K buffer power of the Coorg soils was clearly reflected in the cardamom yield. By comparison, the 1 N NH_4OAc extractable K had no significant relationship with leaf K (Table V) and, further, the integration of the K buffer power in the computations with the routine soil test K data (NH_4OAc extractable K) remarkably improved this relationship.

Cardamom is a heavy feeder of K (Sadanandan *et al.*, 1990), and in India, which grows most of this valuable spice crop, and in other countries on the Asian and African continents, where this crop is grown, its K fertilizer needs are almost always based on the exchangeable K determined by 1N NH_4OAc extraction. Data in Table XXV unequivocally show the inability of this extraction to precisely predict K availability; further, data in Table XXVI show how the situation is remarkably improved by the integration of the

Table XXIV
K Buffer Power of Cardamom-Growing Soils from Two Regions of Southern India Extensively Growing This Crop (After Nair *et al.*, 1997)

Region	Regression function ($Y = a + bx$)	"r"	Crop yield (kg ha^{-1})
Coorg	$142.38 + 1.4443x$	0.8561**	155
Idukki	$592.46 + 0.9712x$	0.5799*	80

Note: "b" values in the regression functions represent the K buffer power of the soil. The K buffer power refers to pooled values of soil samples obtained from 94 locations covering an area of more than 20,000 ha in two cardamom-growing regions of southern India, namely, Coorg and Idukki districts of Karnataka and Kerala States, respectively. Yield data refer to the same locations. The symbols (*) and (**) indicate significance at $p = 0.05$ and 0.01, respectively.

Table XXV
Correlation Coefficients and Regression Functions for the Relationship Leaf K (*Y*) vs Exchangeable K (*x*, NH_4OAc Extractable K) (after Nair *et al.*, 1997)

Details	Regression function ($Y = a + bx$)	Correlation coefficient "*r*"
	Coorg	
Leaf K vs exchangeable K	$Y = 1.2701 + 0.0004$	0.2064
	Idukki	
Leaf K vs exchangeable K	$Y = 1.64448 + 0.000006$	–0.006

Note: The correlation coefficients refer to the leaf samples from 94 locations from which the soil samples were also obtained to calculate the K buffer power. In cardamom the fifth pair of leaves from the top of each panicle bearing tillers are sampled for K analysis (Sadanandan *et al.*, 1993).

Table XXVI
Correlation Coefficients ("*r*") for the Relationship between Leaf K (*Y*) and Exchangeable K (*x*, NH_4OAc Extractable K) for the Pooled Data (94 locations) from Two Regions (Coorg and Idukki Districts of Karnataka and Kerala States, Respectively) Without (A) and With (B) K Buffer Power Integration (Nair *et al.*, 1997)

	Correlation coefficient	
Details	A	B
Leaf vs exchangeable K	0.2510	0.4367**

**Significant at $p = 0.01$ confidence level. Note the remarkable improvement with K buffer power integration into the computations.

K buffer power into the computations. A substantial variation (302.7%) in leaf K is attributable to the K buffer power. These results have been obtained from extensive area (more than 20,000 ha) which demonstrates their significance.

The K buffer power in this instance integrates both exchangeable K (NH_4OAc extractable) and nonexchangeable or interlayer K (HNO_3 extraction) and this gives an accurate measurement of K depletion around the plant roots. In an investigation (Mengel and Uhlenbecker, 1993) on K availability from interlayer K to rye grass (*L. perenne* L. cv. Taptoe), it was observed that the rate constant ("b" values) obtained by correlating K released (from interlayers of clay minerals) and time periods by a modified EUF technique, was closely related to K uptake and represented the K availability index from no exchangeable K. These rate constants, according to the authors, are of the utmost importance because they provide information on the availability of nonexchangeable K in attaining maximum yield; and a set of "critical b" values toward attaining this objective have been reported.

It appears that the rate constants of and Uhlenbecker (1993) are analogous to the K buffer power values reported by Nair *et al.* (1997), because although the techniques differ in their details, they have accomplished the same objective of precisely predicting K availability from the nonexchangeable pool and/or the interlayer K. The capability of tapping interlayer K varies among plant species. For instance, Steffens and Mengel (1979) found that rye grass (*L. perenne*) could feed from interlayer K for a longer period without yield depression, while red clover (*Trifolium pratense*) could not. These authors reported that since *L. perenne* had a longer and deeper root system, compared to *T. pratense*, the former could grow satisfactorily, at relatively low K^+ concentration while the latter would already suffer from K deficiency (Steffens and Mengel, 1981) The differences in root mass, root length and root morphology between monocots and dicots explain the better K^+ feeding capacity from interlayer K^+ of the former compared to the latter (Mengel, 1985).

Cotton, *Gossypium hirsutum L.* is another deep-rooted long duration crop, on which the K buffer power exerts considerable influence on K acquisition. Brouder and Cassman (1994) evaluated K uptake by cotton in a vermiculite soil using a mechanistic mathematical model and observed that initial model output produced both substantial under- and overpredictions of whole-plant K accumulation. Model predictions were greatly enhanced by estimating K buffer power. They further concluded that the contribution of the fixed K pool to the plant available K pool was likely to be substantial and that this influence must be captured in estimates of the K soil buffer power. These studies were conducted after observing in a San Joaquin Valley cotton field in California that cotton exhibited late season K deficiency while other crop species remained unaffected. In such cases, the precise estimation of K buffer power will lead to far more dependable K fertilizer recommendations than estimations by routine NH_4OAc extraction.

Though it has long been recognized (Schachtschabel, 1937) that the soil K fraction, which is not exchangeable by NH_4 ions (non exchangeable K), may be important for the supply of K to plants, it is only of late that researchers have paid more attention to this aspect. The work of Sparks and Huang (1985) has critically examined the release mechanism from nonexchangeable source and the factors controlling it. Considerable portions of initially nonexchangeable K can be utilized by plant roots even within a few days (Kuchenbuch and Jungk, 1984). The depletion zone, however, extends into the ambient soil for 2 mm only. Hinsinger *et al.* (1992) embedded phlogopite in agar and observed that the interlayer K of this mineral was entirely lost in the close vicinity of ryegrass roots within 4 days. Since the process limiting K uptake in the rhizosphere may be K transport through the soil rather than the release from minerals as such, some researchers have focused their attention on this aspect. One such example is the mechanistic mathematical model of Claassen and Barber (1976).

Calaassen *et al.* (1986) and Claassen (1990) have successfully applied the model referred to above to predict K depletion profiles in soil around plant roots. Meyer and Jungk (1993) have used these models to predict K uptake by test plants from exchangeable and nonexchangeable K sources. They reported that 64–79% of the K taken up by wheat (*Triticum aestivum* L.) and sugar beet (*Beta vulgaris* L.) was derived from the rapidly released exchangeable and 21–36% from the nonexchangeable or less mobile soil K fraction.

The buffer power describes the relationship between adsorbed K and the K concentration of the ambient solution. In simulation models it is assumed that this relationship is linear and hence, independent of the soil solution concentration. However, in desorption studies with soil a sharply curved buffer relationship could be found and Meyer and Jungk (1993) have referred to it. Very near the plant roots the soil can be subjected to a curved buffer function since plant roots strongly reduce the soil solution concentration.

An important aspect to be considered in the utilization of nonexchangeable K is the role of plant roots. Plant species differ in their ability to utilize nonexchangfeable K and this has been attributed to the differences in root length (Mengel and Steffens, 1985). Radial distance between two single roots decreases, consequently increasing root density and this would result in the overlapping of the depleted soil volumes between these roots. This would also lead to a decrease in the rate of K uptake per unit root length. In the case of the rapidly diffusing K fraction, which has a higher mobility, the competition effect between roots could be intense. There is evidence to support this view, as shown by the work of Mitsios and Rowell (1987), who observed that the contribution of the nonexchangeable K fraction increased with a corresponding increase in root density. Additionally, the differences in root hair length and density among plant species (Fohse *et al.*, 1991) affect their ability to acquire soil K. Accordingly, the work of Meyer and Jungk (1993) has shown that K uptake was higher when they included root hairs as well in their model calculations. Since root hairs contribute to an increase in root-absorbing surface, a reduction in the distance of the diffusion from the site of K release to the site of K uptake, and an increase in the K concentration gradient, they can be expected to exert a pronounced effect on K availability from the less mobile K fraction.

E. The Commercial Significance of K Buffer Power Determination in K Fertilizer Management for Perennial Crops

The commercial significance of K buffer power determination for dependable K fertilizer recommendation assumes great importance in those countries which are faced with importing these fertilizers at a huge cost to the national exchequer. India is a case in point. The decontrol of phosphate and potassic

fertilizer prices by the Government of India resulted in an overnight escalation of their market prices. In a situation like that, the farmers become extremely wary of their field use and unless the fertilizer application is cost effective, faith in their use, especially those mentioned above, would be shattered.

The K fertilizer recommendation for cardamom has been based exclusively on NH_4OAc extraction. The investigation of Nair *et al.* (1997) showed its ineffectiveness. Although the importance of K buffer power in predicting K availability has been reported earlier, these research reports related to mainly annual crops, such as white clover (During and Durganzich, 1979) and rye grass (Busch, 1982); the work of Nair *et al.* (1997) was the first of its kind in a perennial crop.

One last point regarding the question of accurately predicting K availability is the role of NH_4 ion on K^+ ion. One of the frequent assumptions made in predicting K availability in soils is that results from binary (two-ion) exchange systems can be extrapolated to ternary (three-ion) systems by using appropriate equations. The K–Ca exchange reactions in soils are often investigated in laboratory studies. Most of the research carried out on soil clay minerals and soils as exchanger surfaces (Argersinger *et al.*, 1950; Gapon, 1933; Jardine and Sparks, 1984; Sposito, 1981a,b; Sposito *et al.*, 1981, 1983; Vanselow, 1932) are binary exchange systems. However, field soils are at least ternary systems (Adams, 1971; Curtin and Smillie, 1983). The evaluation of soils as binary systems implies that these reactions can be used to predict results in ternary systems such as field soils. For this assumption to be valid, the binary exchange selectivity coefficients need to be independent of exchanger-phase composition (Lumbanraja and Evangelou, 1992). But, the work of Shu-Yan and Sposito (1981) showed that it is impossible to predict exchange phase–solution phase interactions in a ternary system, such as the field soil from a binary system, such as the laboratory sample. This focuses the importance of the ternary systems. As far as K availability is concerned, it would be important to include NH_4^+ ion as well. The work of Lumbanraja and Evangelou (1992) has shown that K^+ adsorption to soil surfaces is suppressed in the presence of added NH_4^+ ion, while the adsorption of NH_4^+ ion to the same surface is enhanced in the presence of K^+ ion. These observations point to the influence of added NH_4^+ ion on the desorption potential (chemical potential) of adsorbed K or vice versa (Lumbanraja and Evangelou, 1992) and would be relevant to the determination of K buffer power especially when agents containing NH_4^+ ions, such as NH_4OAc, are used in determining K buffer power (Nair *et al.* 1997). The work of Lumbanraja and Evangelou (1992), although, clearly demonstrates the effect of NH_4^+ ion on K desorption, with an increase in K^+ desorption in the presence of added NH_4 ion. In its absence, it might be safe to conclude that the shape of the K buffer power curve will not appreciably change even if larger quantities of K are removed due to cropping and therefore can be considered as a relatively constant property of soils. There is evidence to support this view

(Jimenez and Para, 1991). These authors, while investigating the Q/I relationship with reference to K uptake by wheat (*Triticum aestivum*) in calcareous vertisols and inceptisols of southwestern Spain, found that 80% of the K extracted came from the nonexchangeable K pool. These observations coupled with the one discussed earlier, suggest that the precision of predicting K availability can be substantially enhanced by first quantifying the K buffer power of the soil in which the crop is intended to be grown. Admittedly, the rate-limiting steps involved in the K dynamics are not entirely understood (Sparks, 1987). Notwithstanding this limitation, if one must move forward in devising better management of K fertilizers in crop production, a starting point has to be made with regard to precisely quantifying K availability. Quantifying the K buffer power of soils and basing K fertilizer recommendations on this seems to be the best starting point. The investigations of Nair *et al.* (1997) in a crop like cardamom, which is the second most important spice crop in the world, shows clearly that this can be done.

F. Conclusions

Though cardamom is a perennial crop, its growth behavior resembles that of a biennial crop in the sense that the vegetative phase (tiller production) is preceded to the reproductive phase in the following year when panicle and flower initiation is flowed by fruit set. Since cardamom grows in forest canopy where shade trees also grow, competition for moisture and nutrients from the shade trees should be expected and, hence, water and nutrient management should be controlled intelligently. Following the oil crisis, fertilizer prices have drastically escalated, and it becomes all the more important why economization and enhancement of efficiency of use are important. The relevance of "The Nutrient Buffer Power Concept" is highlighted in this context.

VI. CARDAMOM PATHOLOGY

Cardamom plant is affected by a number of pathogens, of which some are fungi, others bacteria, and yet some others nematodes. These pathogens affect the plant both in the nurseries and main plantations. To date, as many as 25 diseases caused by these agents have been reported. On the basis of severity of damage, these diseases are categorised as major and minor. Considerable damage is caused by four major diseases in the plantations and two in the nurseries. Major diseases, such as the rots, leaf blights, and nematode infestation, are often widespread and lead to crop losses, while minor diseases

generally cause damage to the foliage. Unless properly managed, diseases can cause up to 50% loss to the crop.

A. Major Diseases

Capsule rot (locally referred to as "Azhukal") and the rhizome rot are the ones which cause the most severe damage. Leaf blight and nematode infection lead to weakening of plants and consequent reduction in productivity. Table XXVII lists the major diseases.

1. Capsule Rot ("Azhukal" Disease)

Capsule rot, locally known as "Azhukal" disease (in the South Indian Kerala State, language Malayalam) means rotting. It is the most severe fungal disease of cardamom. Menon *et al.* (1972) reported it for the first time in the cardamom plantations of Idukki district in Kerala State.

a. Geographic Distribution of the Disease. Initially, rotting symptoms are observed on the fruits or capsules, and that is the reason the disease has been named as capsule rot. Subsequently, the disease symptoms are observed in other plant parts. This is the major disease affecting cardamom and causing severe loss of productivity in Idukki and Wayanad districts of Kerala State and Anamalai hills of Tamil Nadu (Thomas *et al.*, 1989). The disease appears following the onset of southwest monsoon. Capsule rot is not observed in the low-rainfall areas of Tamil Nadu. Surprisingly, although Karnataka State receives much rainfall, the disease is still to appear in the state.

Table XXVII
Major Fungal and Nematode Diseases of Cardamom

Disease	Affected plant parts	Causal pathogen
Capsule rot ("Azhukal")	Capsules, leaves, Panicles, young tillers	*Phytophthora meadii, Phytophthora nicotianae var. nicotianae*
Rhizome rot (clump rot)	Rhizomes, tillers, roots	*Pythium vexans, Rhizoctonia solani, Fusarium oxysporum*
Leaf blight ("Chenthal")	Leaves	*Colletotrichum gloeosporioides*
Root knot nematode	Roots, leaves	*Meloidogyne incognita*

b. Symptoms and Damage. Disease symptoms develop mainly on the capsules, young leaves, panicles, and tender shoots. The first visible symptom appears as discolored water-soaked lesions on young leaves and capsules. These lesions enlarge and the affected portions decay. Infection occurs on capsules and tender leaves simultaneously, or, sometimes first on capsules followed by infection of foliage (Thomas *et al.*, 1991a). When foliage is infected, water-soaked lesions appear on leaf tips or leaf margins, which subsequently enlarge and adjacent lesions coalesce to form large patches. Immature unfurled leaf when infected fails to unfurl subsequently. As the disease advances, the lesions on the leaves turn necrotic, followed by leaf decay and shrivel, and finally they look shredded. Infected capsules show water-soaked discolored patches. These turn brownish and later these infected capsules decay and drop off. Foul smell emits from such rotten capsules. Capsules of all ages are susceptible to infection. However, young capsules are far more prone to infection than older ones.

When favorable climate prevails, the disease is aggravated and infection extends to panicles and tender shoots. In severe case of infection, the whole panicle or psuedostem decays completely. In such cases the rotting extends to underground rhizomes also. The root system of such plants gets decayed and following this, the entire plant collapses to the ground. Nair (1979) described similar symptoms and observed that the disease severity is uniform in the three major cardamom types, namely, var. Malabar, var. Mysore, and var. Vazhukka. Nambiar and Sarma (1976) who investigated the disease have reported loss in productivity up to 30%. Subsequently, the loss has been reported to be as high as 40% (Anon, 1989a).

c. Causal Pathogen. *Phytophthora* sp. as the causal pathogen of the disease was first reported by Menon *et al.* (1972). Thankamma and Pillai (1973) identified the organism as *Phytophthora nicotianae* Brede de Haan var. *nicotianae* Waterhouse and *Phytophthora palmivora* Butler (Radha and Joseph, 1974). Nambiar and Sarma (1976) reported the association of *Pythium vexans* and a *Fusarium* sp. along with *Phytophthora* sp. However, subsequent investigations (Nair, 1979) showed *Phytophthora nicotianae* var. *nicotianae* as the causative pathogen, which was successfully isolated from all infected plant parts. *Phytophthora mediaii* Mc Rae has also been widely observed to cause the capsule rot disease (Anon, 1986). Host-range studies show that *Phytophthora palmivora* from coconut and rubber trees can infect cardamom (Radha and Joseph, 1974). Also *Phytophthora palmivora* can infect coconut, cocoa, arecanut, black pepper, and rubber (Manomohanan and Abi Cheeran, 1984). *Phytophthora meadii* from cardamom can also infect black pepper, cocoa, and citrus (Sastry and Hegde, 1987, 1989).

Nair (1979) observed that wild colocasia plants in cardamom plantations serve as collateral hosts for *Phytophthora nicotianae* var. *nicotianae.*

Based on culture characters, sporangial morphology, sexual behavior, and pathogenic virulence, seven different isolates of *Phytophthora meadii* from different localities causing infection on capsules, leafy stems, leaves, and rizhomes have been identified (Anon, 1989a). These seven isolates fall into two groups in their requirement for optimum temperature for growth and mean sporangial dimensions. In single cultures no oospores are formed but when paired with A 1 mating type, five of them readily formed sex organs and oospores confirming that most of these isolates belong to the A 2 mating type. The type species of *Phytophthora meadii* from cardamom readily grows on carrot agar and sporulates; the sporangia are caduceus, ellipsoid, papillate, and with short to medium pedicels. Although these seven isolates morphologically differ only slightly, all of them were found to be pathologically virulent types. The pathogen, *Phytophthora nicotianae* var. *nicotianae* survives in the soil and plant debris in the form of chlamydospores and in moist soil up to 48 weeks (Nair, 1979). However, in the case of *Phytophthora meadii*, no chlamydospore formation has been observed. The inability of *Phytophthora meadii* to form chlamydospores from rubber is also reported.

d. Epidemiology. The epidemiology of capsule rot disease has been studied by Nair (1979). He observed that high disease incidence is correlated to high and incessant rainfall during the southwest monsoon. The number of *Phytophthora* propagules increases in soil and results in heavy disease incidence coinciding with high soil moisture levels (34.3–37.6%), low temperatures (20.4–21.3°C), high relative humidity (83–90.6%) and high rainfall (320–400 mm annual) during the months of June to August (Nair and Menon, 1980). Presence of high level of soil inoculum, thick shade in the plantation, close spacing, high soil moisture, water logging together with favorable weather conditions, such as high relative humidity, continuous rainfall and low temperature predispose the plants to *Phytophthora meadii* infection. Nair (1979) also observed that the density of *Phytophthora* population reduces with increasing distance from the plant base and with depth from soil surface.

2. Disease Management

Since the disease outbreak occurs in the monsoon season, the disease management aspects have to be in place sufficiently early, that is, prior to the onset of primary infection. During earlier years various fungicides have been extensively used to control the disease. Spraying and drenching of

copper fungicides, such as, 1% Bordeaux mixture, 0.2% copper oxychloride (Menon *et al.*, 1973; Nair, 1979; Nair *et al.*, 1982; Nambiar and Sarma, 1974) has been recommended as the disease control measure. Inhibition of the fungus *in vitro* conditions has been reported following treatments with organomercurials (Wilson *et al.*, 1974). Nair (1979) observed 86% reduction in soil population levels of *Phytophthora* when drenched with 1% Bordeaux mixture or 100 ppm Dexon (Bay-5072). Alagianagalingam and Kandaswamy (1981) observed that the disease could be controlled by spraying the plants with 0.2% Dexon (Bay-5072) at the rate of 4 kg ha^{-1}. Although a number of fungicides have been reported to control the disease, often disease control in the field has been a challenging task. Factors responsible for the constraints in achieving satisfactory disease control include lack of adequate phytosanitation, effective and timely application schedules, high cost and nonavailability of fungicides, and the continuous rainfall that makes spraying a difficult operation and reduces its efficacy when the fungicide is sprayed.

Thomas *et al.* (1989, 1991a) evaluated a number of contact and systemic fungicides under field conditions and concluded that two to three rounds of sprays, including one round of prophylactic spray, with 1% Bordeaux mixture or 0.3% Aliette (Fosetyl–aluminum) after proper phytosanitation effectively controlled the spread of the disease.

3. Biological Control of Diseases

Bioagents play an important role in an ecofriendly system of disease management to fight against plant pathogens in a totally safe manner avoiding the use of expensive and hazardous chemical fungicides. Inhibition of *Phytophthora meadii* in laboratory conditions and disease suppression in cardamom nurseries have been investigated by Thomas *et al.* (1991b) employing *Trichoderma viride*, *Trichoderma harzianum*, *Laetisaria arvalis*, and *Bacillus subtilis*. Suseela Bhai *et al.* (1993) achieved field control of capsule rot disease employing *Trichoderma viride* and *Trichoderma harzianum* and have developed further a simple carrier-cum-multiplication medium for *Trichoderma* sp. application in fields (Suseela Bhai *et al.*, 1994, 1997). Cardamom-growing soils in their native state, which harbor *Trichoderma viride* and *Trichoderma harzianum* isolates, have been screened and effective strains for high-biocontrol potential have been developed (Dhanapal and Thomas, 1996). Field control of capsule rot disease has become effective, environmentally safe, and economically cost effective due to the biocontrol potential of *Trichoderma* sp.

4. Rhizome Rot Disease

This disease is also known as clump rot. The onset of the disease occurs during the southwest monsoon. Park (1937) reported the occurrence of the disease for the first time. Subba Rao (1938) described the disease as clump rot. The disease is widely distributed throughout cardamom plantations in the States of Kerala and Karnataka and also in Tamil Nadu where heavy rainfall occurs as in Anamalai hills.

a. Symptoms of the Disease. It is during the southwest monsoon, by about the middle of June, that the disease makes its appearance. The first visible symptom is the development of a pale yellow color in the foliage and premature death of older leaves. These leaves show wilting symptoms. The collar portion of the aerial shoots becomes brittle and the tiller breaks off at the slight physical disturbance. Rotting symptoms develop at the collar region, which becomes soft and brown colored. At this stage the affected aerial shoots fall off emitting a foul smell. Mayne (1942) reported the incidence of the disease in cardamom hills of the State of Kerala. The tender shoots or the young tillers also turn brown colored and rot completely. With the advancement of the disease, all the affected aerial shoots fall off from the base. The panicles and young shoots attached to this also are affected by the rot. Rotting extends to the rhizomes and also roots. Falling off shoots resulting from rhizome rot infection becomes severe during July–August. In severely affected areas, as much as 20% disease incidence is recorded.

b. Causal Pathogen. Subba Rao (1938) observed that cardamom rhizome rot is caused by *Rhizoctonia solani Kuhn.*, and it was associated with a nematode. Ramakrishnan (1949) reported *Pythium vexans* de Barry as the causal pathogen. Thomas and Vijayan (1994) reported that *Fusarium oxysporum* is also occasionally found to cause rhizome rot and root infections.

c. Disease Management. The disease is usually observed in areas previously affected by rhizome rot disease. Therefore, phytosanitation plays an important role in disease management. Presence of inoculum in the soil and plant debris, over crowding of plants, and thick shade are congenial conditions for disease development. Therefore, any disease management schedule has to be followed with these factors in mind. Application of superphosphate at the rate of 300–400 g per plant has been recommended for controlling clump rot in cardamom plantations (Anon, 1955). Soil drenching with 1% Bordeaux mixture or 0.25% copper oxychloride or neem oil cake at the rate of 500 g per plant followed by one round premonsoon and two rounds of postmonsoon soil drenching with 0.25% copper oxychloride at an interval of a month has been reported to be effective for controlling the disease (Thomas and Vijayan, 1994).

d. Biological Control. Attempts in rhizome rot disease control, as in the case of capsule rot, are by taking recourse to the use of *Trichoderma* sp., namely, *Trichoderma viride* and *Trichoderma harzianum* (Thomas *et al.*, 1991b). A formulation of *Trichoderma harzianum* in a carrier medium consisting of farm yard manure and coffee husk mixture has been developed for field application in the integrated disease management system for the control of rot diseases of cardamom (Thomas *et al.*, 1997).

5. Leaf Blight Disease ("Chenthal" Disease)

Chenthal is a leaf blight disease and the name is colloquial (Malayalam language of the State of Kerala, meaning shredding). The disease was first reported by George *et al.* (1976) from Idukki district of the State of Kerala. Since then the occurrence of the disease has been observed in many plantations. The disease spread is faster in partially deforested areas and less shaded plantations. Although it was reported as a minor disease of limited spread, presently the situation is alarming as the disease is spreading to newer areas and is becoming a major problem.

a. Disease Symptoms and Damage. Chenthal appears mostly during the premonsoon period and the severity increases during summer months. Symptoms develop on the foliage as water-soaked rectangular lesions, which subsequently elongate to form parallely arranged streaks. The length of these streaks varies from a few millimeters up to 5 cm. The lesion areas become yellowish-brown to orange-red in color and often the central portions become necrotic. Usually the two youngest leaves are not attacked by the disease. As the disease advances, more and more lesions develop on older leaves, adjacent lesions coalesce, and these areas begin to dry up. Severely infected plants show a burnt appearance. George and Jayasankar (1979) reported reduction in plant height, panicle length, and crop loss due to failure of panicle formation in severely affected plants. However, Govindaraju *et al.* (1996) studied the symptomatology in detail and found that Chenthal infection affects only the leaves and not the plant height, panicle emergence or crop yield.

b. Causal Pathogen. Chenthal was originally reported as a bacterial disease caused by *Corynebacterium* sp. (George and Jayasankar, 1977). They also recommended penicillin spray for controlling the disease. As later investigators could neither isolate *Corynebacterium* sp. nor control the disease with penicillin sprays, the bacterial etiology was suspected, and the cause of the disease remained obscure for more than a decade. Govindaraju *et al.* (1996) conducted detailed investigations on symptomatology, etiology, and management strategies of Chenthal and have clearly shown beyond doubt

that the causal pathogen is the fungus *Colletotrichum gloeosporioides* (Penz.) Penz and Sacc. The fungus closely resembles *Colletotrichum gloeosporioides* causing anthracnose disease of capsule rot reported by Suseela Bhai *et al.* (1988). Both the leaf and capsule isolates showed similar cultural and morphological characters and were cross-infective to capsules and leaves and vice versa. However, these two isolates exhibited considerable differences in their period of occurrence, type of symptoms, distribution and spread of the disease.

c. Disease Management. Since the disease was considered to be caused by *Corynebacterium* sp., penicillin spray was suggested as a control measure for the disease (George and Jayasankar, 1977). However, this was not effective and was abandoned by the planters. Govindaraju *et al.* (1996) reported that three sprays of Carbendazim (Bavistin, 0.3%) at monthly intervals, or Mancozeb (0.3%) or copper oxychloride (0.25%) effectively controlled the spread of Chenthal disease in the cardamom plantations.

d. Diseases Caused by Nematodes. Heavy loss of the crop could be brought about by nematode infestation. Although as many as 20 different genera of plant parasitic nematodes have been reported in cardamom-growing soils (Ali, 1983), only the root knot nematode (*Meloidogyne incognita*), the same which attacks black pepper as well (Nair, 2004), causes the most damage to cardamom. Root knot nematode is widely observed in almost all the cardamom grown regions, both in the nurseries and main plantations (Ramana and Eapen, 1992), while the lesion nematode (*Pratylenchus coffeae*) and the burrowing nematode (*Radopholus similis*) are observed in mixed plantations.

e. Disease Symptoms and Damage. Aerial plant part damages, such as stunting, reduced tillering, resetting and narrowing of leaves, yellow banding of leaf blades, and drying of leaf tips or leaf margins are noticed. The flowering is normally delayed. Immature fruit-dropping results in yield reduction (Anon, 1972, 1989b). Underground symptoms develop on the roots of infected plants in the form of pronounced root galling. Tender root tips show spherical–ovoid swellings. Severe infestation can result in crop losses up to 80% (Ramana and Eapen, 1992). Nematode population is high in cardamom soils during post-monsoon period (September–January). Heavy shade in plantations, moist soil, and warm humid weather are predisposing factors for nematodes to multiply. Nematode infestation is a chronic problem in cardamom nurseries, where the same site is repeatedly used for raising seedlings. Nematode-infested soils affect seed germination and result in severe galling of the root system, marginal yellowing, and drying of leaves, stunting and reduced tillering. The leaves become narrow, and the leaf tips show upward curling.

f. Nematode Control. As infected seedlings serve as the source of inoculum, extreme care has to be taken in transplanting affected seedlings, preferably, avoided as it would be the start of new infection. Pretreatment of infested nursery beds with methyl bromide at the rate of 500 g/10 m^2 or soil drenching with 2% formalin is usually recommended. Solarization of nursery beds is reported to reduce nematode populations in the soil. Nematicides, such as Adicarb, Carbofuran, or Phorate, at the rate of 5 g active ingredient (a.i.) per plant twice a year has been recommended for controlling nematodes in plantations (Ali, 1984). A biocontrol schedule employing *Trichoderma viride* or *Trichoderma harzianum* isolates and also *Pacilomyces lilacinus* to control "Damping Off" disease and nematode damage in cardamom nurseries has been put in place (Eapen and Venugopal, 1995).

B. Minor Diseases

A number of minor diseases, which affect leaves, capsules, and aerial stems, occur sporadically in cardamom plantations. Some of these are frequently observed in all areas, while others are restricted to specific localities. These include various types of leaf spots and capsule spots, stem infections, and so on, caused predominantly by fungal pathogens. Details are given in Table XXVIII.

1. Leaf Blotch

Agnihothrudu (1968) reported a foliar disease in cardamom characterized by the typical blotching of leaves. The disease appears during monsoon season, from June to August, normally under heavily shaded conditions. Thick shade, continuous rainfall, and high atmospheric humidity predispose the cardamom plants to infection. Leaf blotch was thought to be a minor disease. Recently, however, it was found to spread in great severity in certain regions.

2. Disease Symptoms

Nair (1979) has studied in detail symptomatology of leaf blotch. During monsoon, round ovoid, or irregular water-soaked lesions appear on middle leaves, usually near the leaf tips or at the midrib areas. These areas enlarge in size, become dark brown with necrotic center. In moist weather, a thick, gray-colored fungal growth is seen on the under side of these blotched areas. However, the lesion spread is limited in size following a dry period.

Table XXVIII
Minor Fungal and Bacterial Diseases in Cardamom Plantations

Disease	The affected plant part	Causal pathogen
Leaf blotch	Leaves	*Phaeodactylium alpiniae*
Phytophthora leaf blight	Leaves	*Phytophthora meadii*
Phytophthora leaf rust	Leaves	*Pbakospora elettariae* (*Uredo elettariae*)
Phytophthora leaf spot	Leaves	*Sphaceloma cardamomi,* *Cercospora zingiberi,* *Glomerella singulata* *Phaeotrichoconis crotalariae* *Ceriospora elettariae*
Sooty mould	Leaves	*Trichosporiopsis* sp.
Stem lodging	Pseudo stem (tillers)	*Fusarium oxysporum*
Anthracnose	Capsules	*Colletotrichum gloeosporioides*
Capsule tip rot	Capsules	*Rhizoctonia solani*
Fusarium capsule rot	Capsules	*Fusarium moniliformae*
Capsule canker (Vythiri spot)	Capsules	*Bacterium* (?)
Capsule ring spot	Capsules	*Marasmius* sp.
Bacterial rot	Rhizomes	*Erwinia chrysanthimi*

3. Causal Pathogen

Leaf blotch is a fungal disease caused by *Phaeodactylium venkatesanum* (Agnihothrudu, 1969). Subsequently this fungus was identified as *Phaeodactylium alpinae* (Sawada) (Ellis, 1971). The pathogen grows profusely on the underside of the leaves and also grows abundantly on potato dextrose agar medium. Hyphae are hyaline, smooth, partially submerged, 6–10 μ thick, dichotomously or often trichotomously branched with conidia formed at their tips. Conidia are solitary, hyaline with three transverse septa, smooth, elliptical with tapered basal end and broad apices. Conidia measure 15–25 μ × 4.7 μ. The pathogen infects and produces typical symptoms on *Alpinia* sp., *Amomum sp*., and it has been observed that the fungus was completely inhibited *in vitro* conditions by 1% Bordeaux mixture, 0.1% Bavistin, or 0.15% Hinosan (Nair, 1979). Fungicidal spray with copper oxychloride or Bordeaux mixture was reported to control leaf blotch infection in the field (Ali, 1982).

4. *Phytophthora* Leaf Blight

In many cardamom plantations during the postmonsoon season, a widespread leaf blight disease is observed. The infection starts on the young-middle

aged leaves in the form of elongate or ovoid, large, brown-colored patches which soon become necrotic and dry off. These necrotic dry patches are seen mostly on leaf margins and in severe cases the entire leaf area on one side of the midrib is found affected. The disease appears during the winter months of October–November and may extend up to January–February. Thick shade, low-night temperature, and fog prevailing in isolated pockets predispose the plants to leaf blight infection. The causal organism is *Phytophthora meadii*. The pathogen can easily be isolated from infected leaf portions employing water-floating technique. The infection is aerial and the infected plant debris serves as the source of primary inoculum. The pathogen grows internally and under moist and misty conditions produces abundant sporangia, which are disseminated by wind spreading the disease to other areas. Disease symptoms are seen only on the leaves. Although *Phytophthora* is a potential pathogen infecting all parts of cardamom, the leaf blight isolate is seen specific to only leaves under natural conditions. However, cross inoculations of *Phytophthora meadii* leaf isolate on capsules and vice versa were found to be infective on plant parts tested under laboratory conditions.

5. Disease Management

The infection of leaf blight can spread rapidly and leads to severe leaf necrosis and leaf drying if the disease is not controlled in the initial stage itself. One round of foliar spray with 1% Bordeaux mixture, Aliette 0.3%, or Akomin 40 (potassium phosphonate) at 0.3% was found to limit the disease spread.

6. Leaf Rust

A type of rust in cardamom in the state of Karnataka was first reported by Thirumalachar (1943). The disease appears after monsoon during October–May and the disease symptoms appear on leaves in the form of numerous yellowish rusty-colored pustules distributed on leaf surface in several patches. These are mostly seen on the underside of leaves. With the advancement of the disease, pustules or uredosori become reddish-brown in color and they protrude from the leaf surface. The mature pustules break open and release uredospores. In severe cases infected leaves show several yellowish patches with numerous rusty-colored pinhead spots distributed in these yellowish areas of leaf surface. These areas later dry off as the disease advances. The rust fungus *Phakospora elettariae* (Racib.) Cummins (Syn: *Uredo elettariae* Racib.) causes the disease. Naidu (1978) reported a mycoparasite *Darluca filum* (Biv) Cast, hyperparasitising this rust fungus.

The mycoparasite produces dark brown to black-colored pycnidia in large numbers and they protrude from the uredosori. The hyperparasitized uredospores shrivel off and do not germinate. *Darluca filum* develops only in advanced stage of rust development. However, it helps to prevent further secondary spread of the rust fungus. The spread of leaf rust infection can be minimized by spraying fungicides such as Mancozeb 0.2% (Dithane M-45) or Indofil M-45.

7. Leaf Spot Diseases

A number of leaf spot diseases affect cardamom and this is caused by a variety of pathogenic fungi. They infect both the seedling and the mature plant. The types of leaf spots occurring in main plantations are the following.

8. *Sphaceloma* Leaf Spot

The occurrence of this disease in the Coorg district of Karnataka State was first reported by Muthappa (1965). Symptoms appear on leaves in the form of scattered spherical blotches measuring few millimeters in diameter. Adjacent lesions coalesce to form large necrotic patches. This disease was reported as a major problem in Coorg district. Although the disease is present throughout the year, its abundance and severity are more during postmonsoon period. The disease is caused by *Sphaceloma cardamomi* Muthappa. Naidu (1978) reported that Ceylon and Alleppey Green cultivars in Coorg district showed resistance to *Sphaceloma* leaf spots. Cultivars having erect panicles are mostly resistant to leaf spot while cultivars with creeping or prostrate panicles are susceptible.

9. *Cercospora* Leaf Spot

Another leaf spot occurring in Coorg district was reported by Rangaswami *et al.* (1968). Leaf blades show the first symptoms as water-soaked linear lesions, which are rectangular and parallely arranged alongside the veins. On the upper leaf surface, lesions turn dark brown with dirty white long patches in the center. In advanced stages, lesions become grayish-brown in color and later these areas dry off. The disease is caused by *Cercospora zingiberi* Togshi Katsaki. The fungus produces conidiophores in clusters from many-celled dark brown stroma. Conidiophores are simple or branched rarely, septate straight or curved, geniculate, and often undulate at the tip and

light brown colored. The conidiophores measure 17.5–56 μ × 5.23–3.5 μ. Conidia are formed singly, linear, indistinctly septate with three to six septa, mostly curved with obtuse base 37–195 μ × 1.75–2.5 μ. Naidu (1978) observed that cultivars having erect (variety Mysore) panicle are relatively resistant to Cercospora leaf spot compared to variety Malabar having prostrate panicles.

10. Glomella Leaf Spot

Nair (1979) reported the occurrence of a leaf spot disease characterized by the presence of circular–ovoid dark brown, concentric spots on the middle leaves. This disease appears during the postmonsoon period in isolated spots. The disease is generally seen only in variety Malabar. The infection starts as small pale yellow water-soaked lesions on leaves, which may be irregular in shape measuring 1–2 mm in size, which later enlarge in size and form a depressed central area surrounded by a dark band of tissue. Later, alternate concentric dark and pale brown bands develop with a yellow halo around the entire spot. Large mature spots may coalesce and the lesion areas start drying. Sometimes the lesion areas measure as large as about 4 cm in diameter. The fruiting bodies of the fungus are seen as dark brown dot-like structures in the lesion areas.

The causal organism is identified as *Glomerella cingulata* Stoneum Spanding and Shronk. The fungus forms grayish white mycelial growth in potato dextrose agar medium which becomes dark gray with zonations. Acervuli are produced in cultures. Conidiophores are short, hyaline, and conidia are cylindrical, hyaline, and aseptate 12–25 μ × 3–5 μ in size. Perithecia are globose dark brown colored, ostiolate, and measure 85–135 μ in diameter.

11. *Phaeotrichoconis* Leaf Spot

Phaeotrichoconis was reported by Dhanalakshmy and Leelavathy (1976). Symptoms formed on young and old leaves are characterized by irregular papery white spots with brown margins on leaf blade. Under moist conditions the lesions enlarge and coalesce. During dry weather the central portion of lesions dries off. Causal organism is identified as *Phaeotrichoconis crotalariae* (Salam and Rao) Subram. The pathogen grows profusely in culture and produces yellowish-brown mycelium with numerous dark brown sclerotia. Conidiophores are indistinguishable from the hyphae, the conidia are solitary, elongate, fusoid, straight, or slightly curved and five to eight septate.

12. *Ceriospora* Leaf Spot

Yet another type of leaf spot seen rarely on cardamom leaves was reported by Ponnappa and Shaw (1978). This was observed in the Coorg district and is caused by *Ceriospora elettariae* Ponnappa and Shaw. The symptoms are appearance of numerous spots on the foliage, which are circular or oval, up to 8 mm in diameter which coalesce to form larger patches. The lesion center is dirty white surrounded by light brown, circular necrotic areas.

13. Management of Leaf Spot Diseases

Most of the leaf spot diseases described above occur sporadically in minor proportions and as such do not have deleterious effect on crop yield. The spread of these diseases can be prevented by one or two rounds of spraying with common fungicides such as 1% Bordeaux mixture or 0.25% Mancozeb.

14. Sooty Mould

A sooty mould infection on leaves of cardamom growing under the shade tree *Cedrella toona* Roxb was reported by Nair (1979). The disease symptoms appear during January–February months when the shade trees are in blossom. Infection starts as minutely scattered dark mycelial growth on upper leaf surface. This spreads rapidly and covers the entire lamina and in severe cases extends to the petioles and leafy stems, which are later covered with black mycelial growth. In advanced stages, leaves tear off at margins along the veins and dry prematurely. The sooty mould fungus is identified as *Trichosporiopsis* sp.

15. Stem Lodging

In the cardamom plantations of Idukki district in Kerala State, a relatively new disease affecting leafy stem has been found. The same disease has been found in lower Pulney area of Tamil Nadu (Dhanapal and Thomas, unpublished). The disease attacks middle portions of the tillers in the form of pale discolored patches, which lead to a sort of dry rotting. The leafy stem is wakened at this portion and leads to partial breakage. The partially broken tillers bend downwards and hang from the point of infection. Where the infection occurs at the lower part of the tillers, the tillers lodge. In such tillers

leaves and leaf sheaths soon dry up. The disease is caused by *Fusarium oxysporum* and appears usually during postmonsoon period.

16. Anthracnose

Anthracnose occurring on cardamom capsules was reported as a minor disease in certain localities of cardamom cultivation (Suseela Bhai, Thomas and Naidu, 1988). Symptoms appear on capsules as reddish brown round or oval spots of 1–2 mm in diameter, often with a softy depressed center. The lesions vary in number and size and in rare cases coalesce to form large lesions. Often less than 2% of the disease alone is noticed. But in Anamalai areas of Tamil Nadu, as high as 10–28% incidence was noticed.

17. Causal Pathogen

Colletotrichum gloeosporioides (Penz) Penz and Sacc has been shown as the causative pathogen of anthracnose disease (Suseela Bhai *et al.*, 1988). The fungus grows profusely in potato dextrose agar medium producing dark, gray-colored dense mycelium. Setae are dark brown, conidia abundant, cylindrical, straight 12–24 μ × 2.5–5.0 μ in size. A similar infection of *Colletotrichum gloeosporioides* on capsules resulting in the formation of much large lesions often extending up to three-fourth area of the capsules occur in plantations of the Karnataka State. This severe form of anthracnose leads to decay and loss of infected capsules. Fungicides, such as Cuman-L, Foltaf, or Bavistin, when sprayed three times (0.3% concentration) were found to control the disease.

18. Capsule Tip Rot

A characteristic type of rotting of capsule tip is of common occurrence in the State of Karnataka. The disease makes its appearance as small water-soaked lesions at the distal end of the capsule, which later spreads downwards. Infected capsule tip and often up to the middle of the tip, decay. In advanced stages, rotting extends along the entire capsule length. *Rhizoctonia solani* causes the capsule tip rot. A 0.2% spray of bavistin or copper oxychloride or Foltaf checks the disease spread.

19. *Fusarium* Capsule Disease

Wilson *et al.* (1979a) reported a type of capsule disease which *Fusarium moniliforme* Sheld causes. Infection appears as small lesions on capsule rind which later decays and the lesions periphery turns reddish-brown in color.

In the case of severe infection, entire capsules decay during monsoon. The disease symptoms described by Wilson *et al.* (1979) closely resemble that of anthracnose, but *Fusarium* infection often leads to capsule decay.

20. Capsule Canker

A type of capsule spot suspected to be caused by *Xanthomonas* sp. has been reported by Agnihothrudu (1974). This is locally known as Vythiri spot and was initially observed in the district of Wayanad and subsequently the same was observed in several cardamom plantations. Symptoms develop on capsule rind as raised shining blisters or eruptions which are pale to silvery white in color sometimes extending to cover almost half the capsule area. Definitive establishment of the nature of the causal pathogen has not been established, since no pathogenic fungi or bacterium was found associated with these spots. The disease occurs only in minor proportions, which is not alarming as no crop loss has been observed due to infection. However, infected capsules fetch lesser price in cardamom auctions, as these blisters are clearly visible on cured capsules.

21. Capsule Ring Spot

A rare infection of capsules is noticed in certain plantations in the State of Karnataka. The symptoms are characteristic reddish-brown concentric rings or zonations which develop on capsule rind. These areas turn necrotic and subsequently dry off. The infection is suspected to be caused by *Marasmius* sp., although no definitive proof is established.

22. *Erwinia* Rot

Tomlinson and Cox (1987) reported a serious rot disease of cardamom in PNG the symptoms of which are seen on the foliage as yellowing of leaves of mature plants. Rotting and collapse of leafy stems at ground level often accompany this. A pale brown color develops on rhizomes, which later leads to decay of rhizomes. Roots become blackened and necrotic in advanced stages of infection. Infection is observed in the variety Malabar and often leads to collapse of the entire plant.

23. Causal Pathogen

The disease is reported to be caused by a Gram-negative bacterium which has been identified as a strain of *Erwinia chraysanthemi* Burkholder. Tomlinson and Cox (1987) have isolated this bacterium from infected cardamom rhizomes

and roots and were found to be pathogenic. The bacterium has been biochemically characterized and identified as a pectolytic bacterium which readily grows on crystal violet peptone agar (cvp agar). Colonies slightly raised with the appearance of fried egg which have distinct orange-colored center. Pathogenic isolates are KOH soluble Gram-negative rod-shaped bacteria. The bacterium survives in infected rhizomes and roots and also in the rhizosphere.

24. Diseases of Cardamom Found in the Nurseries

The main route of cardamom propagation is through seeds. The seedlings which are raised in nurseries for 10–18 months become plantable. Normally the nurseries are made in two stages, the primary nursery and the secondary nursery. The major diseases occurring in the seedling nurseries are the following (Table XXIX).

a. Damping Off. Wilson *et al.* (1979b) observed the incidence of damping off in young seedlings at the age of 1–6 months. Affected seedlings become pale green and wilt suddenly in masses, as their collar portion rots. Overcrowding of seedlings and excess soil moisture are the predisposing factors of this disease. The causal organism of damping off was identified as *Rhizoctonia solani* (Wilson *et al.*, 1979) and *Pythium vexans* (Nambiar *et al.*, 1975).

b. Seedling Rot or Clump Rot. This disease is similar to the rhizome rot. Normally the disease is observed in nurseries where the seedlings are of 6–12 months age and is often seen during monsoon in overcrowded nurseries.

Table XXIX
Diseases Found to Occur in Cardamom Nurseries

Name of the disease	The affected plant part	Causal pathogen
Primary nursery		
Damping off	Young seedlings	*Rhizoctonia solani, Pythium vexans*
Seed or seedling rot	Seeds, young seedlings	*Fusarium oxysporum*
	Leaf or leaf sheath	*Sclerotium rolfsii*
Seedling rot	Pseudostem	
Leaf spot	Young leaves	*Phyllosticta elettariae*
Secondary nursery		
Seedling rot (clump rot)	Rhizomes, tillers, roots and Leaves	*Pythium vexans, Rhizoctonia solani*
Leaf spot	Leaves	*Colletotrichum gloeosporioides*

Disease symptoms are characterized by wilting or drooping of leaves. Leaves turn pale yellow, followed by rotting of collar of seedlings. As infection advances, the young tillers fall off, and the entire seedling collapses. *Rhizoctonia solani* and *Pythium vexans* are the causal pathogens. Root rot alone affects some nurseries. In such cases, only *Fusarium* sp. was found to be infective. Ali and Venugopal (1993) have reported the association of root knot nematode, *Meloidogyne incognita*, along with *Rhizoctonia solani* and *Pythium vexans*.

Siddaramaiah (1988a) reported the occurrence of seed rot disease resulting in the wilting of seedlings. The disease is caused by *Fusarium oxysporum*. Another seedling disease caused by *Sclerotium rolfsii* which results in the rotting of leaves, leaf sheath, and leafy stem was also reported by the same author (Siddaramaiah, 1988b).

25. Disease Management

Pattanshetty *et al.* (1973) reported that presowing treatment of nursery beds with 2% formaldehyde improved seed germination and reduced damping off disease incidence. Thomas *et al.* (1988) reported fungicidal control of seedling rot and damping off by soil drenching with Emisan 0.2% or Mancozeb 0.4% or Brassicol 0.2%. Seed dressing with *Trichoderma harzianum* followed by one or two rounds of *Trichoderma harzianum* in nursery beds at 30 days intervals has been found to reduce the incidence of seedling rot disease.

26. Nursery Leaf Spot

Leaf spot disease is a serious problem in nurseries amounting to severe loss of seedlings. Subba Rao (1939) reported the disease and subsequently Mayne (1942) identified the causal organism as *Phyllosticta* sp. The pathogen was isolated and studied in detail by Chowdhary (1948) who identified it as *Phyllosticta elettariare* Chowdhary. The disease occurs mainly in the primary nursery on tender leaves as minute water-soaked lesions almost circular in shape with light-colored periphery and a depressed necrotic center. This central portion later dries off and becomes papery white. In later stages, shot holes are formed at the lesion center. As the disease advances, numerous such lesions of different sizes develop and the entire leaf dries off. Several minute dark pinheads like pycnidia of the fungus can be seen in the lesion areas. Older leaves of the seedlings are less susceptible to the disease. As seedlings grow old, they develop resistance to infection and consequently the disease. The disease can easily be controlled by fungicide

sprays, such as 0.2% Difolatan or 0.1% Bordeaux mixture or 0.2% Dithane, when sprayed at fortnightly intervals (Rao and Naidu, 1974).

27. Leaf Spot in Secondary Nursery

A different type of nursery (6–12 months old) leaf spot can be observed. This occurs in the secondary nursery. The disease is characterized by the development of many rectangular water-soaked lesions on the foliage. These lesions enlarge longitudinally and are parallely arranged along the side of the veins. As they mature, they exhibit a muddy red color and become necrotic. The leaves dry off as too many lesions occur side by side. The disease is caused by *Colletotricum gloeosporioides*. A 0.25% Mancozeb spray is effective to control the disease spread.

28. Conclusions

The fungal diseases of cardamom are far easier to control than the devastating viral diseases. However, the use of fungicides and insecticides is being discouraged owing to the strong antipathy of consumers to phytochemicals. The cultivation of organically grown cardamom is gaining importance of late. In view of this, it is essential to evolve biocontrol strategies against the more serious fungal diseases. A protocol for the production of organic cardamom needs to be developed and popularized in order to cater to the demand in international market. Intensive search for natural resistance to the pathogens needs to be initiated. The Western Ghats, being the center for biodiversity for cardamom, the possibility of locating resistance lines is fairly high. Once such resistant gene carrying lines are located, the trait can be transferred to locally grown varieties and cultivars through traditional breeding techniques. Where resistant genes are absent, biotechnological approaches may have to be resorted to, to develop resistant genotypes.

29. Viral Diseases of Cardamom

The major production constraint in cardamom production in India is the occurrence of the mosaic virus (car-MV-*Katte*) disease. Occurrence of cardamom necrosis virus (car-NV-Nilgiri necrosis virus) and cardamom vein clearing disease (car-VCV-Kokke kandu—the colloquial, Kannada language) in some endemic zones are also matters of concern to the cardamom industry. Diseases of cardamom were reviewed by Chattopadhyay (1967), Agnihothrudu (1987), Naidu and Thomas (1994), and Venugopal (1995).

Based on the severity of occurrence and crop losses, four serious viral diseases of cardamom and their integrated management are discussed later.

30. Mosaic or Katte Disease (car-MV)

Locally the mosaic disease is known as "Katte," which in the colloquial language. Kannada of Karnataka State, means disorder. It is known as "marble disease" in Anamalai of Tamil Nadu (Varma and Capoor, 1953).

31. Distribution

Earliest reference on Katte dates back to 1900 by Mollison. In South India, the disease is widely distributed in all cardamom-growing areas, and the incidence ranges from 0.01 to 99% (Mayne, 1951; Venugopal and Naidu, 1981). Until the 1970s cardamom was free of the virus disease. In 1975, a disease with virus-like symptoms was observed in some parts and within 5 years the disease spread to all nearby cardamom plantations in the South-Pacific coastal region, which produces 60% of cardamom in Guatemala (Gonsalves *et al.*, 1986). Surveys conducted in cardamom-growing areas of India on the incidence of car-MV and car-VCV have revealed the prevalence of car-MV in most of the cardamom plantations of Karnataka in South India (Govindaraju *et al.*, 1994).

32. The Extent of Crop Loss

The stage of the plant's growth at which time the infection occurs and the duration the plants are subjected to the infection decides the extent of crop loss. If the plants are infected at the seedling stage or early prebearing stage, the loss will almost be total (CPCRI, 1980; Samraj, 1970). Infection on bearing stage results in gradual decline in productivity (CPCRI, 1984). In cardamom–arecanut mixed cropping systems, crop losses due to viral infection has been estimated at 10–60%, 26–91%, and 82–92%, respectively in the first, second, and third year of production (Varma, 1962a). Similarly in monocrop situations, infection of bearing plants led to yield reductions of 38%, 62%, and 68.7% in the first, second, and third year of infection, respectively (Venugopal and Naidu, 1987). Total decline of plants occurs within 3–5 years from the date of infection.

33. Symptomatology

The first visible symptom appears on the youngest leaf of affected tiller as slender chlorotic flecks measuring 2–5 mm in length. Subsequently these flecks develop into pale green discontinuous stripes. These stripes run parallel to veins from midrib to leaf margins. All of the subsequent emerging leaves show characteristic mosaic symptoms with stripes of green tissue almost evenly distributed over the entire lamina (Uppal *et al.*, 1945). Often mosaic-type mottling is seen on leaf sheaths and young leaf shoots. Variation in field symptoms are seen in different cardamom-growing tracts of South India and on inoculation of different virus isolates on a common host (Venugopal and Naidu, 1981). Plants of all stages of growth are susceptible to virus infection; it is systemic in nature and gradually spreads to all tillers in a clump. In advanced stages, the affected plants produce slender and shorter tillers with only a few short panicles and the plants degenerate gradually.

34. Transmission

Seed, soil, root to root, and manual operations are not the channels for the transmission of the virus (Rao, 1977a,b; Thomas, 1938). The only method of dissemination of the virus is through the banana aphid (*Pentalonia nigronervosa* Coq.), and also through infected rhizomes. The first experimental transmission of Katte virus in India was obtained with banana aphid (Uppal *et al.*, 1945). Up to now, 13 aphid species (*Aphis craccivora* Koch; *Aphis gossypii* Glover; *Aphis nerii* B. de F; *Aphis rumicis* L; *Brachycaudus helichrysi* L; *Greenidia artocarpi* W; *Macrosiphum pisi* Kalt; *Macrosiphum rosaeformis* Das; *Macrosiphum sonchi* L; *Schiazaphis cyperi* van der Groot; *Schiazaphis graminum* Rondm; *Pentalonia nigronervosa* f. *typical*, and *Pentalonia nigronervosa* f. *caladii* van de Groot) were reported to transmit the Katte virus (Rao and Naidu, 1974).

35. Spread of the Disease

a. Sources of Infection. Both infected and healthy clones, seedlings raised in the vicinity of infected plantations, volunteers working in infected plantations, and a few infected zingiberaceous hosts (*Amomum* sp.) are the sources of infection. In a contiguous area, infected plantations are the reservoirs of virus sources (Naidu and Venugopal, 1987, 1989; Varma, 1962a).

b. Primary Spread. In plantations, the primary spread occurs at random due to the activity of viruliferous alate forms of the vector. Under field

conditions, in plantations located 400–600 m from concentrated virus sources, the percentage of primary infection varied from 0.07 to 5.19 (Venugopal *et al.*, 1997a). The frequency of random spread directly depends upon access to virus sources.

c. Secondary Spread. Following the primary spread, secondary spread is mainly internal and the rate of spread is low (Deshpande *et al.*, 1972; Naidu and Venugopal, 1989). Centrifugal influx was found around primary foci due to spread by the activity of apterate adults. In plantations, the disease is concentrated within 40-m radius with occasional random spread up to 90-m distance. Gradient of infection is steep within 40 m from initial foci and it flattens thereafter. In Guatemala, rate of disease spread is fast and natural infection may reach 83% within 6 months of planting. A similar situation exists in the case of cardamom–arecanut mixed cropping systems.

d. Disease-Incubation Period. In the field, the incubation period of Katte disease varies from 20 to 114 days during different months and the expression is directly influenced by the growth of the plants. Normally young seedlings at 3–4 leaves stage express the symptoms within 15–20 days of inoculation, whereas grown up plants take anything from 30 to 40 days for the expression of symptoms during active growing period and 90–120 days during winter months (Venugopal and Naidu, 1987). Senile leaf sheaths which are natural breeding sites of the vector are poor inoculum sources compared to young actively growing shoots (Venugopal and Naidu, 1989).

e. Virus–Vector Relationship. Earlier it was thought that the aphids found on banana and cardamom were the same, but subsequently it was found that *Pentalonia nigronervosa* f. typical breeds on Musa and related genera, while *Pentalonia nigronervosa* f. *caladii* breeds on cardamom, *Colacasia* and *Caladium* (Siddappaji and Reddy, 1972b). In cardamom plantations, the aphid population is seen throughout the year with one or two peak periods during November–May and the population is drastically reduced during the monsoon season. All four nymphal instars and adult are capable of transmitting the disease (Rajan, 1981). Bimodal transmission was examined by using two distinct virus strains with respect to acquisition, latent period, and persistence. Naidu *et al.* (1985) established the nonpersistent nature of the Katte virus.

f. Host Range of the Virus. Several plants which belong to the family Zingiberaceae viz. *Amomum cannecarpum*, *Amomum involucratum*, *Amomum subulatum*, *Alpinia neutans*, *Alpinia mutica*, *Curcuma neilgherrensis*, *Zingiber cernuum*, and a member of Marantaceae (*Maranta arundinacea*, West Indian arrow root) were found infected in the laboratory inoculation tests (Rao and

Naidu, 1973; Siddaramaih *et al*., 1986; Viswanath and Siddaramaiah, 1974; Yaraguntaiah, 1979).

36. Etiology

First evidence of the viral infection was established in 1945. This was achieved through their successful transmission of the virus through banana aphid *Pentalonia negronervosa* Coq. (Uppal *et al*., 1945). Investigations in Guatemala and India have shown the association of flexuous rod-shaped virus particles measuring 650 μ in length and 10–12 μ in diameter in dip and purified preparations (Gonsalves *et al*., 1986; Naidu *et al*., 1985; Usha and Thomas, unpublished). Purified preparations of six strains also revealed homogenous flexuous particles. Presence of inclusion bodies was also reported from leaf tissues of car-MV infected plants. Based on morphology of virus particles and presence of characteristic pinwheel-shaped inclusion bodies, it was suggested to include car-MV in "poty virus" group (Naidu *et al*., 1985). In Guatemala, mosaic-affected cardamom leaves revealed pinwheel type inclusion bodies, which is a common feature in other poty viruses. Leaf dip extracts showed particles of 660 μ length and those of purified preparations showed 700- to 720-μ long particles.

Serological affinity of car-MV of Guatemala with some poty viruses was demonstrated through indirect ELISA test. Four viruses, namely, *Zucchini yellow mosaic*, papaya ringspot types w and p, cow pea aphid borne mosaic virus, and a severe strain of bean common mosaic virus, consistently gave positive reaction in indirect ELISA test. Presence of inclusion bodies, particle morphology, and serological affinity of car-MV has confirmed the inclusion of it in the poty virus group (Dimitman *et al*., 1984; Gonsalves *et al*., 1986). Sequence analysis of the coding regions for coat protein and the 3-untranslated region of the Yeslur isolate (from Saklespur, Karnataka State) placed the Katte virus as a new member of the genus Madura virus of Potyviridae (Jacob and Usha, 2001). Considerable genetic diversity was noted among various isolates (Jacob *et al*., 2002). Some consider Katte as a complex disease caused by more than one component or viruses (Rao, 1977a). So far the studies conducted in India and Guatemala do not support the complex nature of Katte disease.

37. Strains of car-MV

Presence of three natural strains was first reported on the basis of symptomatology on the main host and cross-protection studies (Rao, 1977a). Further, occurrence of different natural strains was reported from the studies

using 68 representative isolates of all cardamom-growing zones of India. Three important biological criteria namely symptoms on the main host, transmission through *Pentalonia nigronervosa* f. *caladii*, and reaction on the set of zingiberaceous differentials consisting of *E. cardamomum* Maton var. Malabar, *Alpinia mutica, Amomum microstephanum*, and *Amomum cannaecarpum* were used to identify the strains (Naidu *et al*., 1985).

38. Cardamom Vein-Clearing Disease or "Kokke Kandu" (car-VCV)

This disease is a new threat to cardamom in some endemic pockets in all the main cardamom-growing areas of Karnataka State. Surveys conducted between 1991 and 1993 indicated the prevalence of car-VCV ranging from 0.1 to 80% in plantations and nurseries (Govindaraju *et al*., 1994; Venugopal and Govindaraju, 1993). It is locally (in the colloquial language Kannada of Karnataka State) referred to as "Kokke Kandu" meaning hook-like tiller.

39. Importance of the Disease

In all the five cardamom-growing districts of Karnataka State, namely, Coorg, Hassan, Chickmagalur, Shimoga, and North Canara, the disease is widely present. In 381 plantations surveyed, widespread incidence of car-MV, car-VCV and mixed infections were seen in 375 plantations with an incidence range of 0.1–82%. A survey in 39 nurseries in hotspots also revealed the incidence of car-VCV.

40. Extent of Crop Loss

Disease-affected plants decline rapidly, and the reduction in yield is to the extent of 62–84% in the first year of peak crop yield (NRCS, 1994). In mixed crop situations with arecanut as the main crop, yield losses vary from 68 to 94% in plants with different stages of infection (IISR, 1995). The affected plants become stunted and perish with 1–2 years after infection sets in and thousands of hectares of cardamom plantations in the Hongadahalla zone in Hassan district and arecanut-based mixed cropping systems in North Canara district (both in the State of Karnataka) have become uneconomical due to infection of mosaic and Kokke Kandu diseases.

41. Symptoms of the Disease

Symptomatic leaves first reveal characteristic continuous or discontinuous intraveinal clearing, stunting, resetting, loosening of leaf sheath and shredding of leaves. Leafy stems exhibit clear mottling in all seasons. Clear light-green patches with three shallow grooves are seen on immature capsules. Cracking of fruits and partial sterility of seeds are other associated symptoms. In summer, the newly infected plants reveal only faint discontinuous vein-clearing symptoms. Plants of all stages, right from seedling to bearing stage show these symptoms. New leaves get entangled in the older leaves and form hook-like tiller; hence the name Kokke Kandu.

42. Transmission of the Disease and Etiology

Car-VCV is not transmitted through seed, soil, leaves, roots, mechanical contact and/or through the use of farm implements. Mechanical transmission on set of differentials through combination of buffers, antioxidants, additives, and abrasives was also not successful (Anand *et al.*, 1998; Venugopal, unpublished). The disease is transmitted through cardamom aphid *Pentalonia nigronervosa* f. *caladii* in a semipersistent manner (IISR, 1996) or persistent manner (Anand *et al.*, 1998). Incubation period ranges from 22 to 128 days and a single viruliferous aphid can transmit virus to plants of all stages of growth. Exact etiology of associated virus is not yet established. In enzyme-linked immunosorbent assay (ELISA test), antigen from infected host parts reacted positively with antibodies raised against poty viruses like peanut mottle virus, sugar cane stripe virus, and Indian and Guatemalan car-MV isolates (Venugopal *et al.*, 1997b). These results indicate that car-VCV is possibly a member of poty virus group.

43. Spread of the Disease

Like car-MV, initial spread occurs randomly in distant blocks due to the activity of incoming alate viruliferous vectors. Random spread was reported in new plantations located up to 2000 m away from infected plantations. Frequency of primary spread is directly dependent on the distance from foci of infection (IISR, 1995, 1996; NRCS, 1994). Secondary spread within the infected plantations is both centrifugal and random. Alate forms of the aphid are responsible for randomspread and apterate forms for the centrifugal spread. In infected plantations, the rate of spread varied from 1.3 to 8.5% per year. Disease spread depends on the distance and level of incidence in the foci of infection. Gradient is steep, concentrated near the sources of

virus inoculum (about 100 m) and it is shallow in the next 100 m (IISR, 1996).

44. Cardamom Necrosis Disease (Nilgiri Necrosis Disease)

The disease was first noticed in severe form in the Nilgiri district of Tamil Nadu, hence, the name Nilgiri Necrosis Virus (NNV). Surveys revealed new pockets of infection in the State of Kerala, Tamil Nadu, and some spots in the Karnataka State. These pockets are located in the Nilgiris district, Anamalai, Cardamom hills, and Bilgiri Rangan hills of Tamil Nadu.

45. Importance of the Disease

Random surveys in South India revealed low incidence of 0.1–1% (CPCRI, 1985). Only in an isolated case in Valparai, in Tamil Nadu, an incidence rate up to 13% was noted. Later surveys in South India indicated that the disease is prevalent in some of the cardamom-growing regions of Tamil Nadu as well, with an incidence rate ranging from 7.7 to 80% (Sridhar *et al.*, 1990). In Lower Pulneys, in Tamil Nadu, out of 24 plantations surveyed, one plantation in Thadiankudisai showed 76% incidence. In Valparai, again in Tamil Nadu, 7.7–15.07% incidence was recorded. Highest incidence of 80% was recorded in Coonor of the Nilgiris district in Tamil Nadu. Some cardamom estates in Munnar and Thondimalai in Idukki district of Kerala State, 4.6% and 1.46% incidence, respectively were recorded. Unlike the Katte disease, the infected plants decline rapidly and become stunted and unproductive.

46. Symtomatology and Crop Loss

Symptoms are seen on young leaves as whitish-yellowish, continuous or broken streaks, proceeding from midrib to leaf margins. In advanced stages of infection, these streaks turn reddish-brown. Often leaf shredding is noticed along these streaks. Leaves reduced in size with distorted margins. Plants infected early, produce only a few panicles and capsules, and in advanced stages of infection, tillers are highly stunted and fail to bear panicles. All the types of cardamom cultivars are susceptible to the disease (Sridhar, 1988).

Plants that are in the early stages of infection recorded less yield reduction compared to those in advanced stages of infection (Sridhar *et al.*, 1991). A 1-year investigation carried out in a diseased plantation indicated 55%

yield reduction in early infected plants and total loss of yield when infection took place late in the crop growth.

47. Transmission of the Disease

Seed, soil, sap, and mechanical injury due to the use of implements do not transmit the disease. It is transmitted through planting infected rhizomes. Aphids, *Pentalonia nigronervosa* f. *caladi*, thrips, *Sciothrips cardamomi*, and white flies, *Dialeurodes cardamomi* were tested for their ability to transmit the disease. No insect transmission of the disease from infected to healthy plants was recorded (Sridhar, 1988).

48. Etiology and Epidemiology

Association of flexuous particles 570- to 700-μ long and 10- to 12-cm broad were seen in dip preparations of NNV infected leaf tissue and it belongs to Carlavirus group (Naidu and Thomas, 1994). Infected rhizomes or seedlings raised from diseased nurseries are the primary sources of inoculum. Monitoring of new infections at regular intervals in a diseased plantation revealed that the spread of the disease is mainly internal and new infections occur in a centrifugal fashion from the source of inoculum. Most of the infections occurred within 10- to 15-m radius from the source of inoculum and the number of new infections decreased as the disease intensity increased (Sridhar, 1988). The pattern of the disease spread is similar to that of Katte disease. The rate of spread of the disease is rather low, being 3.3% for the period in 1 year. Occurrence of a few outbreaks around the infection foci is an indication that the disease can be successfully managed by periodical rouging of infected plants.

49. Infectious Variegation Virus

This disease was first noticed in Vandiperiyar in Kerala State in a severe form. Subsequently it was also noticed in the Coorg district, Hassan, and North Canara of Karnataka State. Disease incidence of 15% was noticed in Vandiperiyar. Infected plants show typical variegated symptoms on leaf with characteristic slender to broad radiating stripes of light and dark green on the lamina. Distortion of leaves, tillers, and stunting are other common symptoms. Within 1 year of infection, the plants become unproductive. Only 2% transmission was obtained through the aphid *Pentalonia nigronervosa* f.

caladii. Roughing resulted in near total elimination of the disease in all the three test plantations.

C. Integrated Management of Viral Diseases in Cardamom

1. Production and Use of Virus-Free Planting Material

On account of several constraints, such as infrastructure, like availability of suitable nursery, plentiful availability of water, accessibility, availability of labor and security, seedlings are raised repeatedly in the same nursery site, year after year, or more commonly in the adjacent area to plantation, which invariably are infected. Seedlings require 10–18 months to attain plantable age. This prolonged exposure to virus access through viruliferous aphids in the vicinity of concentrated virus sources results in infection at nursery stage itself. Further, secondary spread in nursery through aphids results in the spread of virus to many plants. As high as 28% car-MV (Venugopal *et al.*, 1997a) and 73.33% car-VCV (Govindaraju *et al.*, 1994) occur in the nursery stage itself. None of the three virus diseases (car-MV, car-VCV, and car-NV) are seed transmitted, and lack long distance spread beyond 2000 m. Hence, raising nursery in isolated places is necessary to produce healthy seedlings. For car-MV, isolation of 200 m from virus sources is adequate and for car-VCV, isolation of more than 200 m is necessary.

Apparently healthy high-yielding plants are normally subcloned and planted for gap filling and raising plantation (Varma, 1962). As the infected plants take 23–168 days to express car-MV symptoms (Venugopal and Naidu, 1987) and 22–128 days to express car-VCV symptoms (Venugopal *et al.*, unpublished) it is not advisable to use clones from infected gardens. Like nurseries, clonal nurseries also have to be raised in isolated sites. In micropropagation, starting material has to be checked for virus-free status.

2. Avoidance of Volunteers

Volunteers that sprout from remnants of infected materials are the potential primary sources of spread (Naidu and Venugopal, 1987). Self-sown seedlings in the infected plantations are exposed to virus access for 2–8 months. As high as 28% infection was recorded in the nurseries raised from volunteers. Removal of infected volunteers in replanted area and total avoidance of volunteers for nursery activity in hotspots are most important prerequisites for producing virus-free planting material.

3. Movement of Planting Material

In India, surveys conducted in 1981 (Venugopal and Naidu, 1981, 1987) and in 1994 (Govidaraju *et al.*, 1994) have shown that within the infected zone or plantation there are many disease-free pockets. Further, car-VCV is confined to certain endemic pockets only. In Guatemala also, large area is free from mosaic infection (Dimitman, 1981). Creating awareness and preventing the movement of planting material have to be followed to check introduction or reintroduction of viruses.

4. Vector Management

a. *Chemical control*: The nonpersistent nature of car-MV and semipersistent nature of car-VCV render chemical control measures less effective to check or reduce secondary disease spread. The insecticides at recommended concentrations do not kill aphids rapidly enough to prevent probing. Further, persistence of aphid vector throughout the year makes vector control measures almost impracticable. Thirty-four insecticides were evaluated to determine their effect on transmission and acquisition of Katte virus under laboratory conditions. Transmission results showed that none of the insecticides tested were effective in checking acquisition and transmission of the virus even on the day of insecticide application. On account of the nonpersistent nature of car-MV (Naidu *et al.*, 1985; Rao, 1977a,b), it can be transmitted within short periods of probing and feeding. Mere probing is sufficient for transmission of virus. This could be the reason for ineffectiveness of insecticides in checking secondary spread (Rajan *et al.*, 1989). The cardamom aphid, *Pentalonia nigronervosa* f. *caladii*, is photophobic and is found in colonies of 30–50, comprising nymphs, alate, and apterate adults. These colonies are found in between the leafy stems and loose-leaf sheaths especially of old, partly dried, or damaged parts. Occasionally the colonies are found on the leaf spindles, young suckers, and panicles. Because of their concealed placement in the older parts, the possibilities of direct access to contact insecticides and indirect contact to systemic insecticides are less. As a result of insecticide treatment, the colony might have been disturbed and their hyperactivity, probing and intermittent migration in search of suitable hosts, may be responsible for ineffectiveness of some treatment like Phorate (granules), Carbofuran (granules), and Phosphamidon.
b. *Removal of breeding sites*: The photophobic vector breeds in senile, concealed parts of the host (Rajan, 1981). Periodical removal of the old parts of the rhizomatous crop is effective in reducing the aphid population and

the spread of car-MV (Rajan *et al.*, 1989). Other natural hosts like *Colacasia* sp., *Caladium* sp. (Rajan, 1981; Siddappaji and Reddy, 1972a), and so on, which are common weeds in the swampy areas of cardamom plantations, have to be removed periodically to check multiplication of the aphid, in addition to vector control measures.

c. *Use of biopesticides*: Extracts of many botanicals were found to be effective in reducing the breeding potential of aphid vector. Neem products significantly reduced the population of aphids on cardamom leaves even at 0.1% concentration and were lethal to aphids at higher concentrations (Mathew *et al.*, 1997, 1999a,b). Aqueous extracts of *Acorus calamus* L. (dried rhizome), *Annona squamosa* L. (seeds), and *Lawsonia inermis* L. (leaves) reduced the settling percentage of aphids on leaves. Vapors of *Acorus calamus* are highly toxic to aphids and lead to their total mortality. Essential oil of turmeric (*Curcuma longa* L.) was also found to be repellant against the aphid (Saju *et al.*, 1998).
   Entomogenous fungi like *Beauvaria bassiana* (Bals-Criv) Vuill, *Verticillium chlamydosporium* Goddard, and *Paecilomyces lilacinus* (Thom.) Samson were promising in suppressing aphid population without causing hyperactivity (Mathew *et al.*, 1998).
d. *Resistant sources*: All of the 168 germplasm accessions comprising Mysore, Malabar, and Vazhukka types at the Research Center, Appangala, Karnataka State under the administrative control of the Indian Institute of Spices Research in Calicut, Kerala State, which is under the overall administrative control of the Indian Council of Agricultural Research, New Delhi, India, are susceptible to car-MV. Twenty-one elite accessions, distinct morphotypes like compound panicle types are also susceptible (Subba Rao and Naidu, 1981). Seventy natural disease escapes showed field resistance to car-MV in sick plots. They are also high-yielding in character and better than the local cultivar (IISR, 1996, 1997). Screening trial consisting of 24 elite accessions of cardamom against car-VCV in sick plots showed that the accession 893 (of Cardamom Research Center under the administrative control of the Indian Institute of Spices Research) is less susceptible compared to all the other test accessions.
e. *Removal of virus sources*: In the management of plant viruses, phytosanitation involves the detection and elimination of virus sources present within and outside of the cardamom plantations and the efficiency of phytosanitation in management of viral diseases is centered on this operation. Attempts to control the Katte disease spread began as soon as researchers recognized the role of virus and control has been mainly based on sanitation or removal of virus source. Roughing is reported to be effective in minimizing the spread and enhancement of the economic life of plantations (Capoor, 1967, 1969; Deshpande *et al.*, 1972; George, 1967, 1971; Naidu and Venugopal, 1982; Varma, 1962b; Varma and Capoor, 1958).

However, the intensity of disease and the distribution of disease within a plantation are the prime factors influencing the efficacy of roughing. It is more appropriate to adopt roughing as an effective means to contain the spread of the disease in case the disease intensity is less than 10% (Naidu and Venugopal, 1982; Naidu *et al.*, 1985). In general, in plantations, the disease is seen to be concentrated in patches with random spread in certain spots. In such concentrated spots, survey to detect fresh infection and roughing may be undertaken at shorter intervals to minimize the chances of secondary spread (Naidu and Venugopal, 1982). This may be continued for 3–4 months until the new outbreaks of the disease are reduced and thereafter survey intervals can be increased to a few more months. Through sustained timely efforts, new infections can be reduced to 2–3% per annum, although it is impossible to eradicate the disease completely in a plantation because of predominance of small holdings and multiple chances of reintroduction. In contiguous cardamom holdings, isolated attempts are not adequate to contain the disease economically. In such areas community approach through total removal of all the plants followed by replanting and proper surveillance are shown to be more feasible (Varma and Capoor, 1964). In varied field situations, such as new plantation in isolated area, new plantation in hot spots, plantation with unidirectional virus source, plantation with multidirectional virus source, plantation located between two infected plantations and plantation in continuous belt, different approaches involving total removal and replanting, selective rouging and gap filling, phased replanting, and so on, were shown to be effective in reducing secondary spread of the disease.

In car-MV and car-VCV infected areas, there are independent and also mixed infections of both the viruses. In such areas comprehensive efforts involving the use of healthy seedlings, periodical survey through trained disease surveillance gang, prompt removal and destruction of infected plants were reported to be effective in containing both viral diseases (Saju et al., 1997).

f. *Early detection of the disease*: Inoculants take 23–120 days to express the visible symptoms. Early detection of the disease plays an important role in the elimination of further disease spread due to virus sources. Attempts were made to test the polyclonal antiserum produced against car-MV before the expression of the symptoms as well as in the viruliferous aphid vector *Pentalonia nigrovervosa* f. *caladii* for quick detection through ELISA test (Saigopal *et al.*, 1992). Various host plant parts and young and mature seeds of infected and healthy plants were examined. Positive reaction to the presence of the viral antigen was observed before the expression of the symptoms in all the host plant parts except in the mature seeds of infected plants. Virus concentration was more in the roots than in the other plant parts. Testing of viruliferous and nonviruliferous aphid

vectors showed that the viral antigen could be detected in viruliferous aphids. The usefulness of quick detection technique through ELISA test was further confirmed by indexing the primary cultures after *in vitro* multiplication. ELISA tests can be used for rapid field diagnosis of mosaic infection (Roberto, 1982) and in Guatemala, ELISA test is being extensively used in the virus control program (Gonsalves *et al.*, 1986).

g. Integration of several methods, such as strategies to produce healthy seedlings in isolated places, efforts to reduce vector population, use of virus resistant lines and removal of foci of infection are required to manage spread of virus diseases in the field. Establishment of plant disease clinics in potential cardamom-growing areas also help create an acute awareness of the dangers of virus diseases and to impart training to cardamom-growing community to manage the viral diseases. In India, an attempt was made to contain car-MV through the establishment of "Katte Clinics" (Nair and Venugopal, 1982). There was encouraging response from cardamom planters to the initiative and in about 8 months, 60 plantations covering an area of 393 ha distributed in 30 villages of Coorg district in Karnataka State was achieved. In India, the Government of Bombay, during the British rule, attempted to eradicate the Katte disease in North Canara district (now in Karnataka State after the partition of the country into several States) by providing technical assistance to cardamom planters at the cost of the Government of the day (Varma, 1962b). On the same lines now, the Cardamom Board, one of the Agricultural Commodity Boards under the administrative control of the Ministry of Commerce attached to the Government of India, New Delhi, has taken up the eradication of the Katte disease in contiguous blocks in Karnataka State, by providing both financial and technical help to the cardamom planters, primarily for rouging diseased plants. These programs have created awareness about identification and management techniques to contain spread of the viral diseases.

5. Development of Katte-Resistant Cardamom

Intensive survey of the hot spot areas of the Katte disease carried out by the Cardamom Research Center at Appangala in Karnataka State, led to the collection of 138 disease "escapes." This collection included 4 escapes from var. Mysore, 29 from var. Vazhukka and 105 from var. Malabar. A clonal nursery was established from these disease escapes and they were subjected to screening in the green house using virulent virus isolates with the aid of the vector, which showed that 67 collections took the infection, which were then discarded. The escapes from the screening tests were planted in sick plots and the screening continued for 6 years. Most tester lines included in

the trail took infection in 2 years time, but 23 of them remained totally free from the symptoms. Four lines, namely, NKE-11, NKE-16, NKE-22, and NKE-71 expressed faint granular symptoms during the active growth period, but in the following period these symptoms vanished (Venugopal, 1999).

The NKE lines which passed the above detailed screening method were planted in hot spot areas. Nineteen lines remained free from the disease of which 17 had satisfactory agronomic traits. Venugopal *et al.* (1999) investigated the breeding potential of the vector *Pentalonia nigronervosa* f. *caladii* on these 17 lines and compared them with those of a local susceptible check. The aphids colonized and multiplied on all the accessions, thereby indicating that the resistance of the 17 accessions is not due to deterrence to vector but due to some other factors associated with the host.

These 17 lines were further tested after interplanting with known susceptible checks, and they remained free of the disease. Repeated inoculation did not produce any disease symptoms in these lines, thereby confirming the virus-resistant nature of these lines (Venugopal, 1999).

At present, nothing is known about the mechanism of resistance in the above-mentioned resistant lines. Different strains of car-MV have been reported from different virus-infected zones. Some zingiberaceous plants like *Alpinia mutica*, which was found resistant against Kodagu (Coorg), Hassan and Chickmagalur isolates (all from the State of Karnataka), and Wayanad isolate (from the State of Kerala) showed higher susceptibility to Nelliampathy (from the State of Kerala) isolates. Hence, further investigation is important to establish the performance of the above-mentioned virus resistant clones against other distinct virulent strains from different cardamom-growing areas.

6. Conclusions

In cardamom, viral diseases are responsible for rapid degeneration of production potential during the early stages of the establishment of the plantation and cause constant threats to sustainable cardamom production. Only scanty information is available on the characterization of the disease causing viruses. Systematic efforts are required to characterize the viruses and to identify the virus reservoirs within and outside of the crop to reduce the risk of infection in new plantations. Rouging has been reported as available and economical strategy to contain virus infestation. However, continued persistence of infection and recurrence from the sources outside and within the crop is a matter of great concern to cardamom growers, commodity development and promotion agencies. Upgradation of disease management strategies depends on early diagnosis of virus infection in plants at the incubation stage itself and virus carriers. Although there have been attempts made in

Guatemala, India, and so on, application of biochemical and immunological techniques for early detection of the onset of the disease are not being practiced. Successful establishment of the cardamom plantation and its sustained productivity are highly dependent on the production of healthy planting material. Sensitive techniques are yet to be employed in the diagnosis of virus infection and in mass multiplication programs of location specific, high-yielding lines. Similarly, indexing of fast depleting diverse genetic resources is the need of the hour to conserve them appropriately.

A number of lines identified from disease escapes have shown field resistance to car-MV. A clearer understanding of the genetic mechanisms imparting resistance is the only way in the long run to utilize them in cardamom improvement programs through both conventional and biotechnological approaches.

VII. CARDAMOM ENTOMOLOGY

Many insect pests infect the cardamom plant, right from the seedling stage up to the time the produce is cured and stored. Pests limit productivity (Anon, 1985c) and are very destructive. Nearly 60 insect species infest the cardamom plant (Kumaresan and Varadarasan, 1987) at various growth stages of the plant. On the basis of severity of infestation, the pests are classified as major and minor ones (Kumaresan *et al.*, 1988, 1989b; Premkumar *et al.*, 1994). Major ones include thrips, shoot borer, root grub, whitefly and hairy caterpillars, while the minor ones include capsule borers, root borer, rhizome weevil, shoot fly, lace wing bug, cut worm, aphid, scale insects, leaf folder, spotted grasshopper, leaf grub, midrib caterpillar, red spider mites, and storage pests. Kumaresan *et al.* (1989b) classified the pests as foliar, subterranean, and pests on reproductive plant parts, based on the plant parts they infest. At different stages of the plant growth, the pest complex varies.

A. Major Pests

1. Cardamom Thrips [*Sciothrips cardamomi* (Ramk.)]

This is the most destructive of all the pests and it was Ayyar (1935) who first reported its infestation potential in Anamalai Hills of Tamil Nadu and he described it as *Taeniothrips cardamomi*, which was subsequently renamed as *Sciothrips cardamomi*. The nature of the damage and biology of the insect were described by Cheriyan and Kylasam (1941), Kumaresan *et al.* (1988), and Krishnamurthy *et al.* (1989a).

The larvae and adults lacerate tissues from leaf sheaths, unopened leaf spindle, panicles, flowers, tender capsules, and suck the exuding sap resulting in qualitative and quantitative crop loss. Infestation on panicles results in stunted growth, while infestation on flowers leads to shedding of flowers. Laceration of tissues from tender capsules leads to the formation of small scabs, which develop as prominent ugly growths when capsules mature. These scabs generally appear as longitudinal lines over the ridges of the capsules or as patches over them. Such capsules appear malformed, shriveled with slits on the outer skin. The pest-infested capsules do not have the normal aroma and fetch only a poor market price. Unprotected crops may suffer up to 80% damage causing about 45–48% crop loss.

Several field trials have been conducted to evaluate the efficacy of different insecticides in controlling the thrips. Earlier on in these investigations certain organochlorine insecticides were tested which were later abandoned and low doses of organophosphorus and carbamate insecticides were subsequently used. Among the insecticides tested Quinalphos and Dimethoate, each at 0.1% concentration, were found to be effective against thrips (Pillai and Abraham, 1971). Results of a field trial by Kumaresan (1982) revealed that Methidathion, Carbosulfan, each at 0.05% concentration, and Bendiocarb at 0.16% concentration were effective to control the thrips. Kumaresan (1983) tested six insecticides including two synthetic pyrethroids and reported that Permethrin, Fenvalerate, each at 0.01% concentration and Quinalphos at 0.05 concentration when sprayed 8 times in 1 year effectively controlled the thrips infestation. Krishnamurthy *et al.* (1989b) found that an insecticide spray with Monocrotophos/Quinalphos at panicle initiation stage followed by another spray 30–40 days later with Phosalone were found effective against thrips at Mudigere district in Karnataka State. More recently organic compounds have been tried in the control of thrips and detailed investigation on the efficacy of neem (*Azadirachta indica*) formulations, such as neem oil, and other commercial neem formulations were not effective in controlling cardamom thrips (Gopakumar and Singh, 1994).

To combat thrips, the insecticides have to be sprayed only up to the one-third portion of the tillers from the base giving adequate coverage on panicles. Approximately 350–450 ml of spray fluid with a high-volume sprayer may be required for a spray per bush of 50–60 tillers. In times of acute water scarcity, Quinalphos at 1.5% concentration or methylparathion at 2% concentration or Phosalone at 1.5 concentration may be dusted at 25 kg ha^{-1} using dusters. Caution may be taken to harvest the produce either before spraying or at least 2 weeks after the spray. The insecticides recommended to be sprayed for the control of the thrips are listed in Table XXX later.

Table XXX
Recommended Insecticides for the Control of Thrips

Name of the insecticide	Strength at which to be used (%)
Quinalphos	0.025
Fenthion	0.05
Phosalone	0.07
Chlorpyriphos	0.05
Dimethoate	0.05
Acephate	0.075
Triazophos	0.04
Monocrotophos	0.025
Methylparathion	0.05

2. Panicle/Capsule Shoot Borer (*Conogethes punctiferalis* Guen.)

The panicle, capsule, and shoot borer is a serious pest of cardamom in the nurseries as well as in the main field in the southern States of Kerala, Karnataka, and Tamil Nadu. However, infestation is severe in Tamil Nadu and Karnataka States.

Larvae of this pest bore into the panicles or capsules or shoots and grow by feeding on the internal tissues. Infested tillers and panicles dry off and capsules turn empty. The adult is a medium-sized moth with orange-yellow wings having several black dots over it. Eclosion generally happens toward the close of photophase, and the emerging moths rest on under surface of cardamom leaves (Varadarasan *et al.*, 1989). Moths feed on nectar and cause no direct damage to cardamom. A female moth lays about 20–35 eggs singly or in groups of two or three on leaf margins or dry leaf sheath or along leaf veins. Full-grown larvae are pale pink, 30- to 35-mm long and crawl to a place near to the borehole within the shoot. During the ensuing prepupal period of a day or two, they remain quiescent within a self-made cocoon and soon become pupae. After 10–12 days of pupal period, moth emerges through the borehole. The pest population attains peaks during December–January, March–April, May–June, September–October in the conditions prevailing in Lower Pulney of Tamil Nadu, whereas it is highest during January–February, May, and September–October in the conditions prevailing in the Kerala State (Varadarasan *et al.*, 1989).

The pest is polyphagous and a number of alternate hosts, such as mango, guava, mulberry, sorghum, pea, and cocoa exist. In natural conditions *Conogethes punctiferalis* is host for a number of parasites. *Angitia trochanterata* (family *Ichneumonidae*), *Threonia inareolata*, *Bracon brevicornis*, and *Apanteles*

sp. parasitize its larvae, while *Brachymeria emploeae* parasitize pupae (David *et al.*, 1964). Patel and Gangrade (1971) noticed *Microbracon hebetor* as its larval parasite. Joseph *et al.* (1973) reported two hymenopterans *Brachymeria nosatoi* and *Brachymeria lasus* parasitizing on *Conogethes punctiferalis.* Jacob (1981) reported *Myosoma* sp., *Xanthopimpla australis* and a nematode as parasites on *Conogethes punctiferalis*. Varadarasan *et al.* (1990) reported *Temelucha* sp., *Agrypon* sp., and Friona sp. as parasites of *Conogethes punctiferalis.* Natural parasitization by *Agrypon* sp., on larvae of *Conogethes punctiferalis* was maximum (19.8%) during the month of November in Udumbanchola region of Tamil Nadu (Balu *et al.*, 1991).

Several insecticides were evaluated against this pest. Fenthion, BHC, DDT, endrin, malathion, trichlorfan, methyldemeton, Imidan, and Carbaryl were recommended by David *et al.* (1964). However, in a field in Lower Pulneys in Tamil Nadu, 0.1% Monocrotophos was found to be most effective (Kumaresan *et al.*, 1978). Carbofuran at the rate of 2 kg ha^{-1} was found quite effective (Reghupathy, 1979). In addition to the chemical control, physical measures like collection and destruction of affected plant parts, removal of affected tillers in September–October if the infestation is less than 10%, followed by an insecticidal spray of Lebayacid (375 ml in 3000 liter water) or Quinalphos at 0.03%, when the infestation is more than 10% were recommended (Krishnamurthy *et al.*, 1989b). It was found that higher dosage of insecticides was ineffective when late-stage infestation takes place with larvae burrowed inside the shoots.

Root grubs (*Basilepta fulvicorne* Jacoby): Root grub is a serious subterranean pest of cardamom. It damages roots and thereby obstructs uptake of nutrients, which leads to yellowing of leaves and gradual death of plants when the infestation is severe (Gopakumar *et al.*, 1987). The pest affects both the seedlings in the nurseries and in the main plantation and is commonly found in the States of Kerala, Karnataka, and Tamil Nadu in southern India (Varadarasan *et al.*, 1988). It was observed as a very serious pest in Karnataka State (Gopakumar *et al.*, 1987) and Thyagaraj *et al.* (1991) studied the biology and field management of the pest. Adult of the pest is a small beetle 4–6 mm in length and of shiny metallic blue, green, or greenish-brown color. Females are bigger than males. Beetles are polyphagous. The recorded alternate hosts of the beetle are Jackfruit tree (*Artocarpus heterophylla*), Indian almond (*Terminalia catapa*), Mango (*Mangifera indica*), guava (*Psidium guajava*), Ficus (*Ficus indica, Ficus bengalensis*), Cocoa (*Theobroma cacao*), Dadaps (*Erythrina lithosperma*), and so on (Anon, 1993). In plantations, infestation of this pest is observed twice a year, in March–April and August–October, assuming peaks in April and September. Beetles fly about short distances, alight on leaves of shade trees and on cardamom plants. Copulation takes place during daytime and the mated females after a preoviposition period of 4–6 days extrude eggs in groups to a transparent fluid secreted on dry leaf sheaths or leaves, to which they remain glued. Females lay 124–393 eggs in batches of

12–63 during its oviposition period of 8–71 days. Freshly laid eggs are transparent and gradually turn yellow during the incubation period of 8–10 days (at a temperature of 28–31°C) or 13–19 days (at a temperature of 19–24°C) and hatch generally during morning hours liberating small creamy white grubs which fall on the ground, penetrate soil, reach root zone of the plant and start feeding on the roots. Population of the grubs and their infestation is more on cardamom plants under thin shade than those under thick shade. As in the case of beetles, grubs too have two periods of occurrence, first during April–July and second during August–September and December–January, reaching peaks during May–June and November–December.

A judicious combination of both mechanical and chemical methods can control the pest problem (Gopakumar *et al*., 1987). Collection and destruction of beetles at the periods of their massive emergence and subsequent insecticidal control of grubs are the two methods incorporated in the strategy.

During periods of adult emergence (March–April and August–October), beetles alighting on cardamom plants can easily be collected using an insect net and destroyed. During peak emergence of the beetles, 2500–3000 beetles could be collected in a day by a laborer. Such massive destruction of beetles drastically reduces the grub population in the soil to a low level, which would otherwise have been enormous and caused heavy root damage. In endemic areas suitable measures to control the beetle have to be adopted as it becomes virtually impossible to destroy such huge masses of the beetle population. Among the chemical control measures, Varadarasan *et al*. (1990a) reported the application of 20–40 g of Phorate or 0.06% Chlorpyriphos effective in controlling the grubs. Subsequently lowering the dose of Chlorpyriphos to even a lower dose of 0.04% was found effective (Varadarasan *et al*., 1991b).

The pest has been found susceptible to infection of entomopathogenic fungi both at grub and adult stages. *Beauveria bassiana* and *Metarrhizium anisopliae* were isolated from naturally infected beetles and grubs respectively (Varadarasan, 1995). The grubs were also infected by the nematode, *Heterorhabditis* sp. (Varadarasan, 1995). Laboratory studies as well as preliminary field trials with these bioagents have shown convincingly their efficacy and it is expected that a suitable biocontrol strategy could be developed for management of root grubs.

3. Whitefly [*Kanakarajiella cardamomi* (David and Subr.) David and Sundararaj]

Until the 1980s, infestation of cardamom with whitefly was a rare phenomenon and its sporadic occurrence was limited to Nelliampathy and Vandiperiyar areas of Kerala State (Anon, 1980). Now its infestation is seen in many places

in Udumpanchola and Peermedu "Taluks" (colloquial geographical entity) of Idukki district of Kerala State and Lower Pulneys of Tamil Nadu. The species of white flies reported to infest cardamom plants are *Dialeurodes cardamomi* David and Subr. [known as *Kanakarajiella cardamomi* (David and Subr.) David and Sundararaj (1993)], *Aleuroclava cardamomi* (David and Subr.), *Aleurocanthus* sp., *Bemesia tabaci* (Genn.) and *Cockerella diascoreae* Sundararajan and David (Selvakumaran and Kumaresan, 1993). However, only *Kanakarajiella cardamomi* is destructive to cardamom plants.

Gopakumar *et al.* (1988b) and Selvakumaran and Kumaresan (1993) investigated the biology of the pest. Adults produce by parthenogenetic and sexual methods and they live for 7–8 days and they are very much attracted toward yellow color and this behavior is well exploited for trapping them on a yellow surface coated with sticky material. Spraying 0.5% neem oil + triton or 0.5% sandovit on under surface of leaves, twice or thrice at fortnightly intervals during periods of pest infestation is effective against nymphs (Gopakumar and Kumaresan, 1991). Acephate at 0.075%, Ethion at 0.1%, and Triazophos at 0.4% were found to be equally effective in controlling the increase in the number of nymphs (Gopakumar *et al.*, 1988; Selvakumaran and Kumaresan, 1993). Under natural conditions, the pest can be controlled by a number of natural predators like *Mallada bonninensis*, unidentified Neuropteran, Dipteran, Coleopteran and mite, parasitoids, such as *Encarsia septentrionalis* and *Encarsia dialeurodes*, and a pathogen *Aschersonia placenta* (Selvakumaran and Kumaresan, 1993). Potential of these natural predators to control the spread of the pest is totally unexplored in a systematic manner.

4. Hairy Caterpillars

These are a group of defoliators, which appear sporadically and cause severe damage to the crop. Incidence of these pests was reported by Puttarudriah (1955). Nine species of hairy caterpillars are known to infest the cardamom plant. They are *Eupterote canaraica* Moore, *Eupterote cardamomi* Renga, *Eupterote fabia* Cram, *Eupterote testaceae* Walk, *Eupterote undata*, *Linodera vittata* Walk, *Euproctis lutifacia* Hamp, *Alphaea biguttata* Walk, and *Pericallia ricini* Fabr. Biology of different species of these hairy caterpillars was described by Nair (1975), Kumaresan *et al.* (1988). The different *Eupterote* sp. have striking similarities. They are polyphagous larvae which voraciously feed on leaves of shade-trees at early stages and later on, on cardamom leaves.

Adults of both *Eupterote cardamomi* and *Eupterote undata* emerge from their pupae in June following onset of the southwest monsoon. *Eupterote canarica* emerge later. In the case of *Eupterote fabia*, infestation normally

occurs quite late in the monsoon period, by August–October. *Eupterote testaceae* cause only mild damage to cardamom. Its moths have yellowish wings with faint wavy black lines on it. They emerge generally in June–July.

The adults of *Leudera vittata* are thickest with under developed wings and the adults generally emerge in June. The parasite *Carcelia kokiana* is seen to parasitize the larvae (Nair and Kumaresan, 1988). *Euproctis lutifacia* infest tender foliage of cardamom. Adult is a vinous brown moth. After a pupal period of 16–18 days, adults emerge generally during December (Kumaresan, 1988; Nair, 1978). *Alphaea biguttata* is an arctiid black hairy caterpillar infesting cardamom. Its moths are comparatively small. Adults emerge after about 22–23 days of pupation.

Pericalia ricini are medium sized, the dark brown larvae of which emerge after an incubation period of 4–5 days (Kumaresan, 1988; Nair, 1978).

Beeson (1941) reported *Bombax malabaricum*, *Careya arborea*, *Cedrella toona*, *Dalbergia volubilis*, *Erythrina indica*, *Shorea robusta*, *Tectona grandifolia*, *Tectona grandis*, *Terminalia* sp., and *Vitex negundo* as alternate hosts of hairy caterpillars. These caterpillars congregate on tree trunks or cardamom plants during daytime and can be collected in large numbers and destroyed. Sekhar (1959) recommended fish oil rosin soap sprays against the pest. Nambiar *et al.* (1975) found 0.2% BHC or 0.1% Malathion or 0.1% Carbaryl effective to control the pest. Collection and destruction of moths using light traps and spraying 0.1% methylparathion are also recommended to control the pest (Anon, 1985a). The natural enemies of hairy caterpillars reported include *Apanteles tabrobanae* Cram., *Sturmia sericariae, Aphamites eupterotes*, and *Beauveria* sp. (Nair, 1975).

B. Minor Pests

1. Capsule Borers

Jamides alecto: Damage due to this pest, a lycaenid borer, has been severe in Karnataka State at times (Krishnamurthy *et al.*, 1989; Kumaresan *et al.*, 1988; Siddappaji and Reddy, 1972). The caterpillars of the pest bore and feed on inflorescence, flower buds, and capsules. Affected capsules turn empty, decay and drop in the rainy season. Singh *et al.* (1993) investigated the biology of the pest. Adult is a swift flying butterfly having metallic blue color bordered with a white line and black shade on the dorsal surface of wings and with the same color on the ventral surface. The larvae feed on the immature capsules; seeds of ripened capsules are rejected after sensing the seeds. Quinalphos spray at 0.05% or methylparathion spray at 0.05% during early blooming period has been found effective against the pest (Kumaresan

et al., 1988). Application of fish oil rosin soap at the rate of 1 kg in 45 liter water was also found effective against the borer (Kumaresan, 1988).

Thammurgides cardamomi: Adults and larvae of *Thammurgides cardamomi* bore and feed on flowers and immature capsules. In Karnataka, pest infestation is noticeable during July–August especially on plants under thick shade. Adult is a dark brown beetle covered over with short thick hairs. Proper regulation of shade and spray with Quinalphos or methylparathion at 0.05% are recommended for the control of the pest (Anon, 1985a).

Onthophagus coorgensis: This pest bore and feed on flowers and young capsules during monsoon months. They are small, dark brown in color with short thick erect hairs over the body. They lay clusters of barrel-shaped eggs, normally 6–12 in a capsule. The pest can be controlled by proper shade regulation and spraying of Quinalphos or methylparathion at 0.05% (Krishnamurthy *et al.*, 1989b; Kumaresan *et al.*, 1988).

Root borer (*Hilarographa caminodes* Meyer.): Caterpillars of this insect pest bore into the roots and feed on them resulting in yellowing of leaves and gradual dying of plants. Moths emerge during April–May and lay eggs on exposed parts of roots. Emerging caterpillars tunnel into the roots.

Rhizome weevil (*Prodioctes haematicus* Chev. F.): Grubs of this insect tunnel into rhizomes and rarely into aerial stems. Infestation is noticed more on seedlings than on grown-up plants. Adult is a brown weevil 12-mm long having three black lines on pronotum, one middorsally and other two on its either side. On each elytron there are three black dots, two anteriorly and one posteriorly. Adults emerge immediately after receipt of summer rains in April. Adults live for 7–8 months. Destruction of infested plants will help reduce the pest intensity. Drenching 0.2% BHC or soil application of Phorate 10G at the rate of 20–40 g per clump are also recommended against the pest (Anon, 1985a; Kumaresan, 1988).

Shoot fly (*Formosina flavipes* Mall.): This pest is prominent in summer months, which infest seedlings and young tillers under thin shade. Mature flies lay cigar-shaped white eggs singly in rows of four to six between the terminal leaf sheaths. However, only one maggot is seen to penetrate down the pseudostem feeding on core tissues, which results in drying of the terminal unfurled leaf (dead heart symptom). The pest can be controlled by the destruction of infected plants and application of Carbofuran at the rate of 8–10 kg acre^{-1} or by spraying Dimethoate or Quinalphos or methylparathion at 0.05% (Kumaresan *et al.*, 1988). Sufficient shade should be provided to the plants to guard against the pest.

Lacewing bug (*Stephanitis typicus* Dist): This is a bug with shiny, transparent lace-like reticulate wings. Females lay about 30 eggs singly, which are inserted into adaxial surface of leaves. Eggs hatch in 12 days and the emerging nymphs congregate on a suitable feeding site on leaves and suck plant sap resulting in the development of necrotic spots on leaves.

Banana, *Colacasia*, Coconut, and Turmeric are the alternate hosts of this pest (Kumaresan, 1988; Nair, 1978).

Cutworm (*Acrilasisa plagiata* M.): Cutworms are commonly seen to feed on tender cardamom leaves in nurseries. Infestation is noticed in January–March. The fully grown caterpillar is dark brown with orange-red head and a hump-like projection dorsally on the eighth segment. It pupates in soil for a period of 17–18 days (Nair, 1975).

Cardamom aphid (*Pentalonia nigronervosa* f. *caladii* van der Groot): The cardamom aphid is of concern not as a pest of the crop but as a vector of the virus, which causes the most devastating Katte disease. Siddappaji and Reddy (1972a) confirmed the form of the vector occurring on cardamom as *Pentalonia nigronervosa* f. *caladii*. The virus–vector relationship was studied by Uppal *et al.* (1945), Varma (1962a), and Naidu *et al.* (1982). Biology of the insect was investigated and reported by Rajan (1981).

Of the winged and wingless forms of the aphid, the former is longer and slimmer than the latter. Adults are dark brown in color. They reproduce by viviparous and parthenogenetic means. Population of the insect is high in January–February. The insect is also found on *Colocasia* sp., *Alocasia* sp., and *Caladium* sp. The insect population gets drastically reduced during the monsoon season due to the infection of *Verticillium intertextum* (Deshpande *et al.*, 1972). *Peragum indica, Cocinella transversalis*, and *Ischiodon scutellaris* were found to predate the aphids. A spray of 0.05% Phosphamidon or Dimethoate in April and November is recommended to control the aphid (Anon, 1985a).

Scale insect (*Aulacaspis* sp.): Infestation of this pest is noticed during summer. Capsules, panicles, and pseudostems are the usual sites of infestation. The infestation results in the shriveling of the capsules.

Leaf folder (*Homona* sp.): Caterpillars of this pest fold tip of cardamom leaves and feed on the leaves by remaining inside the leaf fold. Fully grown caterpillar is almost 3-cm long, pale green in color with a black head.

Spotted grass hopper (*Aularches* sp.): Adults and nymphs of this polyphagous pest scrape and feed on leaves of cardamom voraciously. Infestation is usually noticed in March, which continues until November. Adult hoppers have pretty green wings with yellow spots on them. Adults congregate on shade tree tops presumably for basking; they descend on cardamom in swarms and defoliate the plants. Exposure of the eggs to desiccation by sun and application of contact insecticides against nymphs are recommended to control the pest.

Leaf grub (*Lema fulvimana* Jacoby): Beetles and grubs of *Lema fulvimana* feed on tender foliage of cardamom seedlings. Biology of the pest was reported by Singh (1994). Beetles emerge in May. Fully grown grubs have a dull white body with brown streaks, black head, and disproportionately

swollen abdomen. Usually they carry the faucal matter on their backs. They pupate in soil inside a papery cocoon. *Zingiber cernuum* and *Curcuma neilgherrensis* are alternate hosts of the pest. Removal of the alternate hosts and spraying 0.025% Quinalphos or 0.025% Monocrotophos is effective in controlling the pest (Singh, 1994).

Metapodistis polychrysa Meyrick: Caterpillars of this insect feed on unopened leaves of cardamom (Gopakumar *et al*., 1989). The caterpillar is pale green and 1-cm long when fully grown. The insect completes its life cycle in 30–35 days.

C. Storage Pests

Tribolium castaneum and *Lasioderma serricorne* are the major storage pests of cardamom. *Lasioderma serricorne* completes its life cycle in about 115 days on stored cardamom (Balu, 1991). Fumigation with methyl bromide or storing the capsules in alkathene-lined jute bags sprayed with 0.5% Malathion is effective in controlling the pest (Abraham, 1975).

Red spider mites: Sporadic infestation by red spider mites on cardamom leaves has been noticed during summer (February–May) in India. The mites remain on the undersurface of leaves within a self-made web. They suck plant sap from leaves resulting in the formation of white blotches on leaves. Undersurface of the infested leaves, with the eggs, excreta of the pest with nymphs embedded in a web of fine delicate silken threads appear ashy white. Affected leaves gradually dry up. Infestation on panicles and tillers is rarely noticed. The mite completes life cycle in about 20 days. Dicofol at the rate of 2 ml liter^{-1} of water or Sulphur 80 wettable powder (WP) at 2.5 g liter^{-1} of water or Ethion at 2 ml liter^{-1} of water or Dimethoate at 1.67 ml liter^{-1} water or Phosalone 2 ml liter^{-1} water are effective chemical control measures.

D. Conclusions

Much information on the biology and control of most of the major and minor pests of cardamom is documented. Most of the control measures are chemical. Rarely are they mechanical. Some parasitoids and predators of certain pests have been identified. The immediate need of the hour is to eliminate most of the insecticides in control measures and substitute plant derivatives and biological control agents. Suitable biocontrol measures must be targeted against the thrips, borers, and root grubs. Excessive dependence on chemicals will bring down the value of the produce in the international market where there is a growing need for organically produced cardamom. There is an urgent need to investigate the potential of bioagents which have

been already identified as effective control measures and the impact of agro-climatic conditions prevailing in the cardamom ecosystem on these bioagents needs further thorough investigation. An integrated pest management (IPM) system with due importance to noninsecticidal means of pest control has to be evolved. To complement this, a keen awareness among the cardamom planters has to be created on the importance of IPM for sustainable cardamom production.

VIII. HARVESTING AND PROCESSING OF CARDAMOM

A. Harvesting

The cardamom plants start bearing 2–3 years after planting seedlings or suckers. Panicles appear from the bases of plants from January onwards and flowering continues from April–August or even later. Generally flowering is highest during May–June. Fruits mature in about 120 days after flowering. Fruits are small trilocular capsules, containing 15–20 seeds. On maturity, seeds turn dark brown to black in color. A healthy cardamom plant, on average, produces annually about 2000 fruits weighing about 900 g, which on drying and curing gives about 200 g marketable produce.

1. Time and Stage of Harvesting

The flowering in cardamom is a continuous process over several months and this results in the capsules ripening successively over an extended period, which necessitates several pickings. Normally harvesting commences in August–September and extends into the next year in February–March. Generally in the peak season, harvesting is done at fortnightly intervals and completed in 8–10 rounds (Korikanthimath, 1983). In Kerala State and Tamil Nadu, harvesting commences from August–September and continues until February–March the following year, while in Karnataka State harvesting starts in August and continues until December–January the following year. Experienced plantation workers do the picking. The physiologically ripened fruits are referred to as "Karikai" in the local language. The maximum dry weight of 285 g kg^{-1} of wet (green) capsules is the recovery rate in Malabar variety, followed by 240 and 140 g recovery in physiologically mature and physiologically immature stages respectively (Korikanthimath and Naidu, 1986). This shows that there is nearly 100% in weight gain from immature to mature stage. Splitting of capsules occur

when harvesting is done at immature stage. Also, essential oil content was found to be more when harvesting was done at mature rather than immature stage.

About 2860 ripe capsules weigh 1 kg, while it takes about 5000 physiologically immature capsules to weigh 1 kg, clearly showing that it is always advantageous to harvest at the right mature stage. When the capsules are well matured, the seeds inside will be black in color.

Two types of picking are practiced—light picking and hard picking. In the first case only matured capsules are picked, while in the second case semimature capsules are also picked. While this would reduce the curing percentage, it would increase the picking average, secure green-colored capsules, and reduce fruit drop and splitting of capsules in the field ensuring minimal loss of the produce. However, the choice of the picking type depends on the availability of manual labor as no mechanical harvesting is practiced in India. Mostly women laborers are employed for harvesting.

a. Postharvest Handling of Cardamom. *Retention of green color*: Color of processed produce is an important factor inasmuch as the consumer is concerned. Most markets, especially in the Middle East countries, prefer green-colored cardamom. The cardamom with the highest quality is "Alleppey Green," still regarded as the best. This comes from the high ranges of the Idukki district in Kerala State, where the predominantly grown variety is Mysore. Investigations have been carried out to understand the mechanism of color retention during the processing of harvested cardamom capsules.

Synthesis and degradation investigations indicate that the total chlorophyll content declines after about 100 days from flowering. Comparative evaluation of chlorophyll contents in dark green, medium and light green capsules have shown that the depth of green color is directly proportional to concentration of chlorophyll content of capsules (Table XXXI). Chlorophyll a is more than chlorophyll b in fresh as well as cured capsules. In husk, 60% of total chlorophyll is present in the surface layer. In the three clones tested,

Table XXXI
The Chlorophyll Profile of Different Capsules

	Chlorophyll content (ppm)			
Capsule color	a	b	Total	a/b Ratio
Light green	509 (186)	561 (167)	1070 (352)	0.9 (1.1)
Medium green	727 (384)	700 (349)	1424 (731)	1.0 (1.1)
Dark green	1677 (446)	1890 (382)	3567 (828)	1.12 (1.2)

namely, Thachangal, Mudigiri, and PV1, total chlorophyll content was more in 100 days old capsules of Thachangal (2186 ppm) followed by that of Mudigiri (1756 ppm) and least in PV1 (1488 ppm) (Anon, 1991). The above investigation suggested that dry matter continued to increase until capsules reached maturity while chlorophyll content started declining after 100 days from flowering (Anon, 1991). The decline in chlorophyll content during postripening period is more in Mudigiri (variety Malabar) compared to varieties Vazhukka and Mysore indicating that delay in picking of this clone could affect the final greenness of capsules (Anon, 1991).

To retain the green color of the harvested capsules, various chemical treatments have been tried because the green-colored capsules fetch a high premium in the market. Among such treatments, soaking the green (wet) capsules immediately after harvest in a 2% sodium carbonate solution for 10 min fixes the green color during subsequent drying and storage (Natarajan *et al.*, 1968). Immature capsules retained greater intensity of the green color. Meisheri (1993) has developed a dehydration unit, which can retain the green color and dry the produce rapidly at ambient temperature (27–40°C).

b. Predrying Operations. Capsules after harvest are washed thoroughly in water to remove adhering soil before taking them to drying kilns. In different trials conducted earlier, it was found that presoaking (quick dip) of capsules in hot water at 40°C and dipping the capsules for 10 min in 2% sodium carbonate had helped in better retention of the green color of cured capsules. Dipping capsules in hot/warm water at lower temperatures, namely, 30°C and 35°C also was tried. Additives like 2% sodium carbonate in warm/hot water (particularly 35°C) helped to increase the green color of the capsules. Dipping in hot water may arrest the activity of certain enzymes. Volatiles extracted from capsules presoaked in hot water and sodium carbonate solution were subjected to GLC analysis. Results indicated that there were no significant changes in oil profile due to hot water or sodium carbonate treatments (Anon, 1991).

Presoaking of capsules in copper formulations and chemicals like naphthalene acetic acid, IAA and gibberlic acid, and magnesium sulfate helped retain more chlorophyll compared to other treatments. However, when presoaking time was extended to 60 min, significant depletion of chlorophyll was observed in all, except in ascorbic acid treatment. Other treatments, namely, urea, 2,4-D, Cycocel at 100 ppm each, kinetin at 10 ppm, glycerol at 5%, and polyethylene glycol at 5% recorded either no effect or marginal negative effect on stability of chlorophyll (Anon, 1991).

Chlorophyll degradation takes place on exposure to sun, and bleaching of green color takes place. Post harvest delay prior to curing is known to cause chlorophyll breakdown, a better storage system could help to minimize such chlorophyll loss.

Various trials conducted to study the impact of precuring storage indicated the following.

1. Capsule cured immediately after picking retained more of the green color.
2. Loss of the green color was more significant if capsules were stored for more than 12 h from the time they were picked.
3. Bagging capsules helped to minimize the rate of loss of green color.

To store fresh capsules jute bag was found most ideal compared to polypropylene woven bag. Storage of fresh capsules at low temperature was found to reduce postharvest precuring loss of the green color. Capsules stored in low energy or zero energy cool chambers were found to be distinctly greener than the capsules stored in the open. In large cardamom plantations, two reinforced concrete cement tanks constructed adjacent to each other are used, one for initial washing of the capsules to remove dirt and soil particles adhering to them and the other for washing with washing soda. Following washing, capsules are spread in a single layer in portable drying trays for draining water. Subsequently, the trays are arranged in kilns for drying.

B. Curing

Cardamom capsules at harvest, depending on the degree of maturity, carry moisture levels of 70–80%. For proper storage, the initial moisture level has to be brought down to 8–10% (on the basis of wet weight) by curing. Curing also plays an important role in preserving green color of the capsules since as much as 60–80% of the initial color is lost while processing. The most widely adopted system is a slow or passive process stretching from 18 to 30 h, with an initial temperature around 50°C. The entire curing time can be divided into four stages.

Stage	Time lag
I	0–3 h
II	3–6 h
III	6–9 h
IV	9 to final curing

Both the degree of maturity and curing temperature influence the percentage of splits in cured capsules. However, temperature has a greater influence (Anon, 1991). During the process of curing, if the temperature exceeds the threshold levels or the inflow of air is insufficient, capsules develop brownish streaks as a result of heat injury. In the case of fairly high temperature, oil from seeds oozes out. Maintaining the temperature at 40°C in all the four stages of curing process helps in greater retention of the green color.

Percentage of split and discolored capsules increases with rise in temperature. Curing at 55–60°C significantly increases the percentage of yellow capsules.

The husk of raw capsules contains about 80% water, which has to be removed completely in the process of drying. Maximum loss of chlorophyll occurs in the initial 6 h of curing. Higher air flow rates increase the loss of chlorophyll. Lesser energy is required for extraction of moisture in the initial stages when the evaporation is from the surface layers of capsules. Comparatively greater energy is required to remove the same amount of moisture when moisture content of capsules falls in the later stages of curing. Cardamom oil extracted from samples dried at 45°C and 60°C did not show much difference in the GLC profile (Anon, 1991). Cardamom capsules are moderately hygroscopic and absorb and desorb moisture depending on the changes in the ambient relative humidity and moisture. Two types of drying are generally adopted, namely, natural sun drying and artificial drying using fire wood, fuel, or electricity. Drying operation demands heavy input of energy. Energy required to dry 1 kg of green cardamom at 100% efficiency can be used to light 250 bulbs of 100 W each for 1 h.

1. Sun Drying

Sun drying is generally undesirable for cardamom. When cardamom capsules are sun dried, there is a bleaching effect due to the action of UV light present in sunlight. Sun drying requires 5–6 days or more depending upon the availability of sunlight. As the capsules are frequently turned during sun drying, capsules split. Cloudy atmosphere and frequent rains hinder proper sun drying. The method of sun drying is prevalent among small plantation owners in Sirsi district and surrounding places in the State of Karnataka.

2. Artificial Drying

a. Electrical Dryer. A dryer having dimensions of 90 cm × 84 cm is more common. Uniform heat distribution is ensured by means of fans. In this way 50 kg of fresh capsules can be dried in 10–12 h and medium green-colored cardamom can be obtained by drying at 45–50°C.

b. Pipe Curing (Kiln Drying). This is one of the best methods of drying to obtain high-quality green cardamom. The structure usually consists of walls made of bricks or stones and tiled roof with ceiling. A furnace is situated on one side of the chamber and heat is generated by burning farm waste. The fire in the furnace is maintained to maintain temperature between 45°C and 50°C and by this method high-quality green cardamom can be prepared in 18–22 h. A drying chamber of dimension 4.5-m length and 4.5-m

breadth is sufficient for a plantation producing 1800–2000 kg of raw cardamom. Some of the kilns make use of brick constructed heat conveyer lines (Kachru and Gupta, 1993).

3. Bin Dryer

This is a dryer designed by the University of Agricultural Sciences, Bangalore, Karnataka State, India. Drying unit consists mainly of a blower with motor, electrical heating unit, and drying chamber. The drier is made of mild steel, asbestos sheet, and wood. Aluminum or steel trays of 0.4 m $\times$ 0.6 m size can be arranged one over the other. Cardamom capsules are to be spread uniformly on these trays. Hot air passing through pipes increases temperature from 30 to 80°C. Good quality cardamom can be produced by drying capsules at 55°C by maintaining the volume of air at 3.7 $m^3\ s^{-1}$. Cost of drying by this method comes to about less than 1 cent per kg compared to about 2 cents per kg in the conventional method (Gurumurthy *et al.*, 1985).

4. Melccard Dryer

This is a fire wood operated dryer commonly used in some parts of Tamil Nadu. It consists of a fully insulated (fire bricks with mud coating) oven kept at 3 m below the dryer. The hot flue gas from the oven is passed to an iron tank through insulated pipes. All the trays carrying cardamom capsules move smoothly on rails fixed inside the dryer. Trap doors attached can be opened periodically to clean off the soot formed in the interior of the flue pipes (Palaniappan, 1986). Dried capsules are rubbed by hand or with coir mat or wire mesh and winnowed to remove other plant residues and foreign matter. They are then stored out according to size and color.

5. Cross-Flow Electric Dryer

This is a tray-type cross-flow dryer having capacities ranging from 25 to 400 kg. The air is heated 15-kW electric heaters and circulated over the material by 0.5 hp electric fan. The drying time requirement at full loading condition is about 18–20 h (Kachru and Gupta, 1993).

6. Solar Cardamom Dryer

Direct type solar drier developed by Central Plantation Crops Research Institute at Kasaragod in Kerala State, for copra (dried coconut ball without

outer shell) drying can also be used for cardamom. The dryer has an area of 1 m^2 drying surface made of black painted wire mesh tray over black painted corrugated GI sheet inclined at 12.5°. The aluminum foil relectors of 1.5 m^2 are provided from three sides of the drier. Material load density can be three times than that used in open drying system. Complete drying of cardamom could be achieved within 3 days using this dryer in comparison to 5 days in the open sun. Bleaching of cardamom capsules due to the action of UV rays in sunlight is a disadvantage of this dryer.

7. Mechanical Cardamom Dryer

Developed by the Regional Research Laboratory in Trivandrum, Kerala State, this dryer consists of a centrifugal blower, electrical furnace, conducting arrangement for uniform hot air flow, and a drying chamber. It can be used for cardamom drying at a load of 120 kg fresh cardamom/batch. It takes about 22 h for complete drying at a temperature of 50°C. The final product is claimed to possess superior green color, flavor, and appearance (Kachru and Gupta, 1993).

8. Through Flow Dryer

This is fabricated by the Central Food Technology Research Institute, Mysore, Karnataka State. The drier consists of a centrifugal blower, electrical furnace ducting with arrangements to distribute the flow of hot air uniformly and a drying chamber where 120 kg fresh cardamom capsules can be loaded to a bed thickness of 20 cm. The air velocity at 60 cm s^{-1} and the drying temperature was thermostatically controlled. The hot air carrying the humidity was not allowed to recycle. It was found to take about 22 h to complete drying of 120 kg fresh capsules at a temperature of 50°C. As the cardamom plantations are generally located in forest areas where electricity is not available, flue pipe dryers are more dependable and suitable to ensure continuous working. There is still good scope in developing a dryer ideal to produce green capsules without any volatile oil loss and with minimum expenditure for drying.

9. Bleached Cardamom

Bleached cardamom is creamy white or golden yellow in color. Bleaching can be done either with dried cardamom capsules or freshly harvested capsules as starting material.

a. Bleaching of Freshly Harvested Capsules. Fresh capsules soaked for 1 h in 20% potassium metabisulfite solution containing 1% hydrogen peroxide solution degrade the chlorophyll. Drying of these capsules yields golden yellow color.

b. Bleaching of Dry Capsules

Sulfur bleaching: It involves sulfur fumigation with alternate periods of soaking and drying. Capsules are soaked in 2% bleaching powder (20 g liter^{-1} of water) for 1 h and spread on wooden trays, which are arranged inside airtight chambers. Sulphur dioxide is produced by burning sulfur (15 g kg^{-1} of capsules) and made to pass over the trays. The process of soaking and drying is repeated three to four times depending upon the intensity of white color required.
Potassium metabisulfite bleaching: In this method capsules are treated with 2% potassium metabisulfite containing 1% HCl for 30 min. Further they are transferred to a 4% hydrogen peroxide solution for 6 h.
Hydrogen peroxide bleaching: Hydrogen peroxide at low concentration (4–6%, pH 4) can bleach capsules in 6–8 h of soaking. These capsules are then dried to 10–12% moisture content. Bleached capsules contain sulfur which protects cardamom from pests. However, it was found that bleaching led to loss of volatile oil.
Conventional bleaching: In Karnataka State, bleaching of cardamom is carried out by steeping the dried capsules in soap nut water. The fruits of soap nut (*Sapindus saponaria*) are mixed with water in a large vessel and stirred vigorously to produce plenty of lather. Dried cardamom capsules are then steeped in this water with occasional stirring. After 1 h or so the fruits are collected in wicker baskets, water is allowed to be completely drained off, and then spread out in mats for drying. Clean water is occasionally sprinkled over the cardamom capsules. The process of sprinkling water and drying is continued for a couple of days till a good quality bleached product is obtained. In general, bleaching of dried capsules lead to loss of volatile oil probably because the bleaching process makes the husk brittle. However, bleached cardamom has white appearance and is resistant to weevil infestation due to sulfur dioxide content (Govindarajan *et al.*, 1982; Krishnamoorthy and Natarajan, 1976).

C. Moisture Content

Moisture content of commercial samples from market ranges from 7 to 20% depending on the regions and mode of curing (Varkey *et al.*, 1980). It is found that 10% moisture is ideal for the retention of green color, which also

depends on the type of drying. Well-dried capsules produce a typical tinkling sound on shaking.

D. Grading

The quality requirement of a produce varies with the primary raw material producer, intermediary collector, the trader, exporter, importer, processor, distributor, and final consumer. Moisture level, cleanliness, content of sub standard product, extraneous matter, appearance, and color determine the final quality of a product. The processor values the extractives, volatile oil, and specific ingredients. Specifications are restricted to attributes, which can be simply and rapidly analyzed. Many of them are related to physical parameters, such as, color, size, weight per specified volume, freedom from microbial, insect, and filth contaminations (Govindarajan *et al.*, 1982b). Specifications for Indian cardamom varieties are given in Table XXXII.

Alleppey Green cardamom is the dried capsule of *E. cardamomum* grown in South India, kiln dried, which has reasonably uniform shade of green color, three cornered and having a ribbed appearance. Coorg clipped cardamom is the dried capsules of *E. cardamomum* variety Malabar grown in Coorg in Karnataka State. Its color ranges from pale yellow to brown, global in shape, skin ribbed or smooth. The pedides are separated. Bleachable white cardamom is the fully developed dried capsule of *E. cardamomum* grown in the State of Karnataka to a reasonably uniform shade of white, light green or light gray color and suitable for bleaching.

In India "Agmark" grades are commonly used to specify quality of products. The Agmark grades of Coorg clipped cardamom and bleachable white cardamom are given in Tables XXXIII–XXXV.

E. Bleached and Half Bleached Cardamom

Cardamom should be fully developed, dried capsules, bleached or half bleached by sulfuring; color should range from pale cream to white, globose, or three cornered with skin ribbed or smooth.

Allepey cardamom seeds are the decorticated and dry seeds of *E. cardamomum* grown in Coorg and adjoining districts of Karnataka State. The specifications are given in Table XXXVI.

Following are some of the general specifications for cardamom.

1. The capsules should be well formed, packed with sound seeds inside. The cardamom may be graded on the basis of place of origin, color, size, mass per liter, bleach level, proportion of lower grades, and extraneous matter.

Table XXXII
Specifications (Physical Characteristics) for Indian Cardamom Varieties

Grade	Description	Size (mm)	Weight minimum (g liter^{-1})	Color	General characteristics
AG, Alleppey Green					
AGB	Extra bold	7	435	Green	Kiln dried, three cornered, and with ribbed appearance
AGS	Superior	5	385	Green	Same as above
AGS 1	Shipment	4	320–350	Light	
AGL	Light	3.5	260	Green	
CG, Coorg Green					
CGEB	Extra bold	8	450	Golden to light green	
CGB	Bold	7.5	435		
CG 1	Superior	6.5	415	Light green	Round, ribbed or smooth skin
CG 2	Mota Green	6	385	Green	
CG 3	Shipment	5	350	Cream	
CG 4	Light	3.5	280	Brown	
Bleached or half bleached					
BL 1		8.5	340	Pale	Fully developed
BL 2		7	340	Creamy	Round, three cornered, ribbed or smooth skin
BL 3		5	300	Dull white	

Source: Indian Standard Specification for Cardamom. IS: 1907–1966. Indian Standards Institution, New Delhi.

Table XXXIII
The Agmark Specifications of Coorg Clipped Cardamom

Grade designation	Trade name	Empty and malformed capsules by count (max. %)	Unclipped capsules by count (max. %)	Immature and shriveled capsules by weight (%)	Size (mm)	Weight minimum (g liter^{-1})
CCS 1	Bold	5.0	0.0	0.0	8.5	435
CCS 2	Coorg Green or Mota Green	5.0	3.0	4.0	6.0	385
CC 3	Shipment	3.0	5.0	7.0	4.0	350
CC 4	Light			3.5	260	

Table XXXIV
The Agmark Specifications of Bleachable White Cardamom

Grade designation	Trade name	Empty and malformed by count (max.)	Immature and shriveled by weight (%)	Size (mm)	Weight minimum (g liter^{-1})
BW 1	Mysore/Mangalore bleachable cardamom clipped	1.0	0.0	7.0	460
BW 2	Mysore/Mangalore bleachable cardamom unclipped	1.0	0.0	7.0	460
BW 3	Bleachable bulk cardamom clipped	2.0	0.0	4.3	435
BW 4	Bleachable bulk cardamom unclipped	2.0	0.0	4.3	435

Table XXXV
Agmark Specifications of Mangalore Cardamom Seeds

Grade designation	Trade name	Extraneous matter by weight (%)	Light seeds by weight (%)	Weight minimum (g liter^{-1})
MS 1	Prime	1.0	3.5	675
MS 2	Shipment	2.0	5.0	460
MS 3	Brokens	5.0		

Note: Extraneous matter: Includes calyx pieces, stalk bits, and other foreign matter. Light seeds: Includes seeds brown or red in color and broken, immature and shriveled seeds.

Table XXXVI
Agmark Specifications of Alleppey Cardamom Seeds

Grade designation	Trade name	Extraneous matter by weight (%)	Light seeds by weight (%)	Weight minimum (g/l)
AS 1	Prime	1.0	3.0	675
AS 2	Shipment	2.0	5.0	460
AS 3	Brokens	5.0		

2. The aroma and taste of cardamom in capsules and seeds should be characteristic, fresh, and free from foreign aroma and taste, including rancidity and mustiness.
3. Cardamom capsules and seeds should be free from living insects, moulds and should be practically free from dead insects, its fragments, and rodent contamination.
4. The mass of cardamom capsules or seeds contained in 1 liter should be as specified for different grades.
5. Cardamom should be free from visible dirt or dust. Extraneous matter, such as bits of calyx, stalks, and others, shall not be more than 5% by weight in cardamom capsules and 0.5–2% by weight in different grades of cardamom seeds.
6. The proportion of empty or malformed capsules, from opening and examining 100 capsules taken from the sample, should not be more than 1–7% by count, varying with grade specifications.
7. The proportion of immature and shriveled capsules separated according to specified methods should not be more than 2–7% (m m^{-1}).
8. Capsules having black color and those which are split open at corners for more than half the length should not be found in bold grades, and not more than 10% and 15% by count in the "shipment" and "light" grades.

Table XXXVII
The Physical and Chemical Specifications of Whole Cardamom

Specification	Suggested limits
ASTA cleanliness specifications	
Whole dead insects by count	4
Mammalian excreta (mg lb^{-1})	3
Other excreta (mg lb^{-1})	1.0
Mould (% by weight)	1.0
Insect defiled, infested (% by weight)	1.0
Extraneous matter (% by weight)	0.5
FDA DALs	None
Volatile oil	3% minimum
Moisture	12% maximum
Ash	10% maximum
Acid insoluble ash	2% maximum
Average bulk index (mg/100 g)	
Bleached	320
Green	250

Table XXXVIII
The Physical and Chemical Specifications of Ground Cardamom

Specification	Suggested limits
FDA DALs	None
Volatile oil	3% minimum
Moisture	12% maximum
Total ash	10% maximum
Acid insoluble ash	2% maximum
Military Specifications (EE-S-631J, 1981)-Decorticated Cardamom	
Volatile oil (ml/100 g)	3% minimum
Moisture	12% maximum
Total ash	7% maximum
Acid insoluble ash	3% maximum
Granulation	95% minimum through a US$40
Bulk index (2 ml/100 g)	190

9. The proportion of cardamom seeds which are light brown, broken, or immature (shriveled) should not be more than 3–5% (m m^{-1}).

The chemical and physical specifications for whole and ground cardamom are given in Tables XXXVII and XXXVIII.

F. Commercial Cardamom Grades in Sri Lanka

Most of the cardamom produced in Sri Lanka is exported. The traders use various designations for cardamom such as the ones given later (Guenther, 1952).

1. Green cardamom
   Kandy type: Relatively large, dark greenish in color
   Copernicus type: Slightly smaller than the Kandy type, generally green in color
   General faq. Type: Small cardamom, grayish green in color
2. Bleached cardamom: Malabar half-bleached: Fair and of average quality, small capsules
   Curtius: Fair in size, rather long capsules
   Cleophas: Fair in size, roundish capsules
3. Seeds
   Crispus type: Freshly removed seeds obtained by the dehusking of either green or bleached capsules

In general, the trade distinguishes between decorticated cardamom, green cardamom, and bleached cardamom.

G. Grading and Packing

Cardamom, which is sun dried or dried in a dryer, has to be protected from absorption of moisture, contamination with extraneous matter which might impart unpleasant odor, microorganisms, and insect infestation. The specific requirement of packing cardamom is the protection of the product from sunlight in order to maintain the husk color, green, or golden color of the bleached cardamom. Cardamom is a high-value crop, the second most important spice crop of the world, and every care has to be taken to efficiently process and grade it, besides curing. Sieves of different mesh sizes, namely, 6,7, 7.5, and 8 mm are available for sieving which have to be manually operated. After sieving the capsules and grouping them into different grades, it is essential to sort out the "splits," thrips and borer-infested capsules separately. Presently sorting is done by skilled women laborers. As the harvest alone demands about 60% of the labor force, there is an urgent need to fabricate mechanical sorting machines in order to obtain the produce of different sizes, with provision to separate out capsules infested with insects and the "splits."

Cardamom needs to be stored for a specified period of time after grading. The graded produce is normally stored in double-lined polyethylene bags. The quality of the stored material could be impaired by storage pests. Hence, there is also an urgent need to devise storage systems to minimize storage pest infestation.

Equilibrium relative humidity studies have shown that cardamom dried and maintained at or below 10% moisture retains the original color and precludes infestation by moulds (Govidarajan, 1982). If black polyethylene is used to store the produce, the adverse effect of light is further minimized and safe storage is possible for 4 months, required for port storage and transshipment. It is advisable to make use of the dried cardamom capsules preferably within 12–15 months of harvest, failing which the pleasant flavor and aroma are likely to be adversely affected. The stored samples must be frequently tested for storage pests.

H. Conclusions

Close monitoring of the various operations, right from harvesting to drying and final grading is required to obtain quality end produce. Initial moisture that the capsules release while drying should be removed immediately by providing cross ventilation and exhaust fans. Any breakdown in the heat energy supply affects the appearance and quality of the produce. Excessive heat adversely affects the quality of the cardamom capsules. Even in the pipe dryers, where heat is generated by firewood, a mechanism should be developed to regulate temperature suitably. The small and marginal farmers, who constitute nearly 70% of the cardamom growers, face difficulties in processing their own drying kilns due to economic constraints. Since cardamom estates are located in deep interior forests, transport of wet capsules to distant places causes much practical difficulties. Hence, there is an urgent need to design and fabricate an efficient cardamom dryer involving comparatively lesser cost and which can provide efficient drying facility.

Cardamom capsules need to be dried within 24 h of harvest, and any delay would result in deterioration of the green color and appearance. It is uneconomical to operate cardamom dryers with smaller quantities of the harvested produce. Hence, research efforts need to be made to store wet capsules for 2–3 days without impairment of quality. Use of nonconventional energy sources for drying cardamom merits consideration in the fast changing agroecological conditions of cardamom tracts of India. Exploration of locally available farm wastes and their biorecycling to generate heat energy merits immediate attention.

IX. INDUSTRIAL PROCESSING OF CARDAMOM AND CARDAMOM PRODUCTS

Cardamom, which is traded, is the dried fruit (capsule) of the cardamom plant. It is processed into various products such as cardamom seeds, cardamom powder, cardamom oil, cardamom oleoresin, encapsulated cardamom flavor, and so on. Proper maturity with good characteristic aroma

and high-volatile oil content are the prime considerations for processing cardamom into various products. Although cardamom is mainly sold as the dried capsule, both in the national and international markets, there is some demand for cardamom seeds in the American and Scandinavian markets. Shelf life of cardamom seeds is poor because the aromatic volatile principle is present in a single layer just below the epidermis. The flavor of cardamom is entirely due to its volatile oil content and flavor strength is directly related to the quantity of oil present in it. Hence, a suitable packaging material has to be employed to store seeds. On the other hand, cardamom capsules with the husk intact can be stored for a year without the loss of any volatiles (Gerhardt, 1972; Guenther, 1952). Whole cardamom does not deteriorate in storage because of the natural protection of the outer cover. Cardamom is stored in gunny bags (jute bags lined with 300 gauge polyethylene and sometimes packed in wooden chests lined with moisture proof kraft paper or polyethylene).

Cardamom seeds, powder, volatile oil, oleoresin, and encapsulated flavors obtained from cardamom are the important products in the trade. Industrial processing and related technological aspects of these products are discussed here.

A. Cardamom Seeds

The cardamom seeds are obtained by decorticating the dried capsules. Decortication is done by using a flour mill or plate mill, which is also known as disc mill. The distance between the discs plays a crucial role in the decortication process. The gap is adjusted in such a way that only husk is detached without damaging the seeds. With proper disc adjustment there should only be minimum loss of the material during the dehusking operation. Good quality seeds will be black to brown in color. The seeds of variety Malabar are sweet to taste due to the presence of a sweet mucilaginous matter (Purseglove *et al.*, 1981). The quality specifications for cardamom seeds are the following (Table XXXIX).

Table XXXIX
Quality Specifications for Cardamom Seeds

Component (%)	Requirement	Country
Moisture (maximum)	9.0	USA, UK
Volatile oil (minimum)	4.0	ISO, Sri Lanka, UK, India IS: 1797–1961
Total ash (maximum)	5–6	USA, UK
Acid insoluble ash (maximum)	3–3.5	USA, UK

Source: Govindarajan *et al.* (1982).

B. Packaging and Storage of Cardamom Seeds

Much greater attention is required in the storage of cardamom seeds than storage of dried capsules. This is because unlike in the case of capsules where there is a natural protection given to the seed by the husk, this is not available in the case of seed. Bulk packaging of seeds is done in wooden chests lined with aluminum foil laminate. Loss of oil from seeds is reported to be as high as 30% in 8 months under ambient conditions, while from dried capsules the loss is negligible (Guenther, 1952). Clevenger (1934) observed that there was 30% loss of volatiles from the seeds in 8 months storage. The importance of distilling seeds immediately is well understood and Table XL summarizes the details of volatile oil distilled. Freshly harvested and processed capsules gave an yield of 9.8% while capsules after exposure to air for 1 month yielded only 2.9% volatile oil, which indicates a loss of 70% of oil. The loss of oil from ground seed is rapid when not properly protected and in 13 weeks' time only traces of volatile oil were found in the seed.

Griebel and Hess (1940), Gerhardt (1972), and Koller (1976) have reported the effect of different storage conditions on the rate of oil loss from seeds and ground cardamom and, Koller (1976), in particular, mentions that the temperature of storage has a greater influence on the rate of oil loss rather than the type of container or the period of storage.

C. Cardamom Powder

Cardamom in its powder form gives the maximum flavor to the food products. But, the disadvantage with powder is that it loses its aroma by rapid loss of

Table XL
Effect of Storage Periods on the Yield of Cardamom Oil

Type of material	Yield of volatile oil (%)
Freshly gathered whole fruit	9.8
Seeds exposed to air for 1 month	2.9
Seeds exposed to air for 6 months	2.4
Seeds exposed to air for 14 months	2.0
Seeds exposed to air for 1 week	2.4
Seeds exposed to air for 6 weeks	2.4
Seeds exposed to air for 13 weeks	Traces
Seeds freshly removed from capsules	4.8
Ground seeds exposed to air for 1 week	2.4
Ground seeds exposed to air for 13 weeks	Traces

Source: Mahindru (1978); Wijesekera and Nethsingha (1975).

volatiles. Hence, the powder needs more protection than the whole capsules or seeds. The industrial and institutional requirements of cardamom are met by grinding seeds just before use (ITC/SEPC, 1978; ITC, 1977).

D. Grinding

Grinding is an important step in the process of converting a spice into powder, and one has to be very cautious with a spice-like cardamom because it has very delicate aroma. The aroma principles of cardamom seed are present near the surface and hence, more attention is needed during grinding because of the heat produced in attrition. The temperature during grinding can go up to as high as 95°C in mass production (Pruthi, 1980; Wistreich and Schafer, 1962). For grinding, conventional mills like plate mill or hammer mill or pin mill are employed. The particle-size of the ground spice may vary from 250 to 700 μ, while as a flavorant for addition in food products the preferred size will be 250–300 μ. Finer particle size helps in easy release of aroma and better mixing with food products.

Investigations on griding of cardamom at ambient conditions, using plate mill, and low temperature, using centrifugal mill, were carried out by Gopalakrishnan *et al.* (1990). In ambient conditions, using 0.25-mm sieve led to loss of volatiles to the extent of 52.8%, while using 0.50-mm sieve, the loss was restricted to 34%. However, with a coarse powder obtained by using 0.75-mm sieve, loss of volatiles was seen to be lowered to 26.2%, but when 1-mm sieve was used with coarser powder, the trend in the loss of volatiles was reversed. The higher loss or poor recovery in the latter case was attributed to the incomplete release of oil from the very coarse powder. Grinding of frozen cardamom seeds or grinding seeds with liquid nitrogen using 0.25-mm sieve resulted in 35.4% and 37.8% loss of volatiles, respectively. However, cryogrinding seeds with dry ice gave the best results and the loss of volatiles was only 8.74%, but during the grinding moisture absorption by the material was noticed. Other studies have also shown that the loss of volatiles was considerably minimized by prechilling the spice and grinding at low temperature (Anon, 1975, 1977).

Cryogrinding or freeze grinding of spices is a novel approach to get better spice powder of better quality along with enhanced retention of votalies (Wistreich and Schafer, 1962). Advantages of cryogrinding are minimum oxidative losses of volatiles, increased output of the powder (end product) and prevention of gumming up of screens or discs during milling (Russo, 1976). The product so obtained has good dispersibility in food preparations. It is also reported that low temperature reduces microbial load on spices. The cost of cryoprocess gets reduced when milling operations are carried out on a bigger scale and with efficient recycling of the refrigerant.

Maximum yield of oil has been obtained when the cardamom seeds are precooled by using liquid nitrogen to a temperature range of −180°C to −190°C and grinding the seeds to a size of 250 μ, which is, indeed, a fine powder size.

E. Storage Powder

Ground cardamom loses its aroma quality rapidly by loss of volatiles and hence proper care should be taken during storage. Gerhardt (1972) found that lacquered cans, PVDC and high-density polyethylene (HDPE) were suitable for storage of powder. Koller (1976) found that vacuum-packaged ground cardamom stored at 5°C retained flavor for longer periods. Polyester/aluminum foil/polyethylene laminate, with its outstanding moisture, oxygen, and odor barrier properties can offer a long shelf life of over 180 days under normal conditions for cardamom powder. For shorter storage life of 90 days and below, metalized polyester/polyethylene laminate can be considered.

F. Cardamom Oil

Cardamom oil is obtained by distillation of powdered seeds of cardamom. Steam distillation is the most common method employed for the production of cardamom oil. Use of the cohabitation technique for distillation has been discontinued due to the hydrolysis of esters during the process of operation. The quality of oil depends on the variety, rate, and time of distillation. The important trade varieties are Alleppey Green, Coorg Green, and Saklespur bleached. Yield of volatile oil from the seeds of these three varieties was 10.8%, 9.0%, and 8.0%, respectively (Lewis *et al.*, 1967). External appearance, size, or bleached color are not the parameters to be considered while selecting cardamom for distillation. The high-grade cardamom is not economical for distillation, since it fetches a better price as whole cardamom in the trade. Lower grades, which do not fetch higher value because of defective appearance, but still good from the point of view of flavor, are ideally suited for distillation. The husk is almost devoid of any volatile oil (Anon, 1985). The flavor of cardamom is mainly due to 1,8-cineole, terpinyl acetate, linalyl acetate, or linalool (Table XLI). The total flavor profile is given in Table XLII.

The United Kingdom was earlier distilling oil from the cardamom obtained from India, Sri Lanka, and Tanzania (British Pharmacopoeia, 1980, 1993). The oil used was termed "English distilled cardamom oil" and

Table XLI
The Flavor Profile (Main Components) of Cardamom Oil

Components	Content (%)	Trace components	
α-Pinene	1.5	Hydrocarbons	Alcohols and phenols
β-Pinene	0.2	α-Thujene	3-Methyl butanol
Sabinene	2.8	Camphen	*p*-Menth-3-en-l-ol
Myrcene	1.6	α-terpinene	Perillyl alcohol
α-Phellandrene	0.2	*cis*-Ocimene	Cuminyl alcohol
Limonene	11.6	*trans*-Ocimene	*p*-Cresol
1,8-Cineole	36.3	Toluene	Carvacerol
y-terpinene	0.7	*p*-Dimethylstyrene	Thymol
p-Cymene	0.1	Cyclosativene	Carbonyls
Terpinolene	0.5	α-Copaene	3-Methyl butanal
Linalool	3.0	α-Ylangene	2-Methyl-butanal
Linalyl acetate	2.5	y-Cadinene	Pentanal
Terpinen-4-ol	0.9	y-Cadinene	Furfural
α-Terpineol	2.6		8-Acetoxycarvotanacetone
α-Terpinyl acetate	31.3	Acids	Cuminaldehyde
Citronellol	0.3	Acetic	Carvone
Nerol	0.5	Propionic	
Geraniol	0.5	Butyric	Others
Methyl eugenol	0.2	2-Methyl butyric	Pinole
Trans-nerolidol	2.7	3-Methyl butyric	Terpinyl-4-yl acetate
			α-Terpinene propionate
			Dihydro-α-terpinyl acetate

Table XLII
The Composition of Different Varieties of Cardamom

Variety	Husk (%)	Seeds (%)	Volatile oil in seeds (%v/w)
Kerala State			
Alleppey Green	26.0–38.0	62.0–72.3	7.5–11.3
Karnataka State			
Coorg	25.2–28.0	69.6–73.3	7.5–9.1
Tamil Nadu			
Yercaud	24.0–33.0	73.0–76.0	6.5–9.6

Source: Data compiled from Nambudiri *et al.* (1968); Shankaracharya and Natarajan (1971).
Note: Moisture in the above-mentioned raw materials ranged from 8 to 12%.

priced higher compared to the oils produced from these cardamom-growing countries. With the advent of better technology for the distillation of cardamom oil, the production of oil in the United Kingdom has been considerably reduced, and the oil is being imported now.

G. Industrial Production of Cardamom Oil

Cardamom capsules of proper maturity which have moisture content of 10–12% are selected for oil distillation. The capsules are cleaned with a destoner (which removes small stones mixed with the capsules) and air classifier to remove undesirable extraneous matter. The cleaned capsules are dehusked in a disc (plate) mill. The gap between the discs is critical in order to avoid damage to seeds. Seeds and broken husks are separated in a vibratory sieve. The average composition of capsules of different varieties of cardamom is given in Table XLII.

Cardamom seeds free of husk are passed through the plate mill wherein the gap between the discs is brought closer to get coarse powder to pass through a 2-mm sieve. The oil glands exist just below the epidermal layer, and hence great care should be exercised while powdering. Fine milling should be avoided to prevent loss of the volatiles. The powdered material is subjected to distillation as quickly as possible. If, for any reason, there is delay in distillation, the ground powder is packed in airtight containers until it is used. Distillation for a 500 kg batch powder usually takes 5–6 h and may even go up to 10 h. The rate of distillation and the condensate temperature are carefully regulated, and it has been observed that keeping the condensate warm helps in clear separation of oil from water (Nambudiri *et al.*, 1968). After commencement of the distillation, in the first 1 h about 60–70% of the oil is collected. It has been observed that early fractions are rich in low-boiling terpenes and 1,8-cineole and the subsequent fractions are rich in esters like terpinyl acetate (Krishnan and Guha, 1950). Between varieties Malabar and Mysore, the former contains much larger amounts of 1,8-cineole content and this makes it more harsh and camphoraceous, while the oil from the latter has a sweet and fruity floral odor due to the lower amount of cineole and higher amounts of terpinyl acetate, linalool and linalyl acetate (Lewis, 1973). Variety Mysore is the largest selling Indian cardamom, named Alleppey Green.

H. Improvement in Flavor Quality of Cardamom Oil

Flavor quality of cardamom oil containing high amounts of 1,8-cineole has been improved by fractional distillation (Narayanan and Natarajan, 1977). The authors in their experiment subjected 200 g of cardamom powder for distillation and in the first 2.5 min collected 6.5 ml oil, of which 78.86% was 1,8-cineole and traces of α-terpinyl acetate. In the subsequent period of distillation, in the time range of 2.5 min to 2 h, of the 10.5 ml collected, 47.5% was 1,8-cineole and 36.8% α-terpinyl acetate. Hence, it is possible to get good quality cardamom oil by using inferior grade cardamom by

suitably collecting the oil fractions at different intervals of time. Careful blending of the fractions is carried out by keeping the aroma profile and specifications in view. The oil yield will be less by about 25% by this method but will be economical since the subsequent fraction fetches a higher price. The specification of cardamom oil is given in Table XLIII.

Raghavan *et al.* (1991a) have standardized a method for the separation of 1,8-cineole from cardamom oil by adduct-formation using orthophosphoric acid. In this method 100 ml of cardamom oil is first treated with 30 ml of orthophosphoric acid and then with 50 ml petroleum ether with constant stirring. The adduct (precipitate) formed is then filtered. The precipitate is air dried and extracted with 500 ml of hot water. Cineole fraction is released as a separate layer and recovered. The aqueous layer is extracted with 200 ml of petroleum ether and desolventized to get terpinyl acetate rich fraction. The gas chromotagraphy analysis of these fractions showed that cineole fraction (28 ml) contained 80% cineole and 18% terpinyl acetate while the terpinyl acetate fraction (58 ml) contained 76% terpinyl acetate and 16% cineole.

Table XLIII
The Specification for Cardamom Oil

Definition, source	Volatile oil distilled from the seeds of *Elettaria cardamomum* (Linn) Maton; family; Zingiberaceae; cardamom grown in South India, Sri Lanka, Thailand, Guatemala, South China, and Indonesia
Physical and chemical constants	Appearance: colorless to very pale yellow liquid. Odor and taste: aromatic, penetrating, somewhat camphoraceous odor of cardamom; persistently pungent; strongly aromatic taste. Specific gravity: 0.917–0.947 at 25 °C (temperature correction factor 0.00079 $°C^{-1}$). Optical rotation: +22° to +44°. Refractive index: 1.463–1.466 at 20 °C
Descriptive characteristics	Solubility: 70% alcohol: in 5 volumes; occasional opalescence: benzyl alcohol: in all proportions diethyl phthalate: in all proportions fixed oil: in all proportions glycerine: insoluble mineral oil: soluble with opalescence propylene glycol: insoluble stability: unstable in presence of strong alkali and strong acids; relatively stable to weak organic acids; affected by light
Containers and storage	Glass, aluminum, or suitably lined containers, filled full; tightly Closed and stored in cool place, protected from light

Source: Adopted from EOA, 1976.

Oil yield from husk is reported to vary from 0.2 to 1% and the oil possessed similar properties as that of seed oil (Rao *et al.*, 1925; Rosengarten, 1969). Nambudiri *et al.* (1968) have found that husk does not give more than 0.1% volatile oil while the reported higher values may be due to the admixture of seeds along with the husk during sieving operation. The chemical quality of the oil obtained from seeds and husk was evaluated by Verghese (1985) using GLC and IR methods. Although there was excellent correlation and the spectra were super imposable, the organoleptic profile differed. The author concluded that distillation of oil from seeds along with husk is detrimental as it is likely to impair the flavor spectrum of the oil. Purseglove *et al.* (1981) mentions that oil obtained from green and bleached cardamom will be similar in composition.

Hydrodistillation of cardamom is not practiced commercially because the distillation time is more and the release of oil is slow due to gelatinization of starch besides hydrolysis of the esters present in the oil (Wijesekera and Nethsingha, 1975). Another disadvantage is, the resulting mass after hydrodistillation is not easily amenable for oleoresin extraction with solvents.

I. Storage of Cardamom Oil

Cardamom oil before storage should be free of trace amounts of moisture, and this is accomplished by addition of any hydrous sodium sulfate. The oil is stored in aluminum containers. Polyethylene terepthalate (PET) bottles that possess very good odor barrier properties can also be considered. Food grade high molecular weight high-density polyethylene (HMHDPE) containers are also being used. The oil is filled to capacity of the container and stored at 8–10°C and protected from light.

J. Cardamom Oleoresin

Oleoresin is made of two components, namely, volatile oil and resin. The former represents the aroma while the resin is made up of nonvolatile matter like color, fat, pungent constituents, waxes, and so on. The total flavor effect of a spice is obtained only after blending the oil with resin. Volatile oil is obtained by steam or hydrodistillation while the resin is obtained by solvent extraction. Of late, super critical fluid extraction (SCFE) is also being adopted.

Demand for cardamom oleoresin is rather limited unlike that obtained from black pepper. Cardamom oil itself represents almost all the aroma and flavor of the capsules. The consumption of cardamom oleoresin is slowly picking up probably due to its mellower and less harsh flavor characteristics

(Sankarikutty *et al.*, 1982). Although the cardamom oil represents the flavor of cardamom, it lacks the "richness" which is attributed to the absence of nonvolatile components (Lewis *et al.*, 1974). Sensory differences have also been noticed between oils and oleoresins of cardamom (Govindarajan *et al.*, 1982b).

For oleoresin extraction, either freshly ground cardamom or essential oil-free cardamom powder (cardamom powder from which oil has been distilled off) is employed. The main considerations involved in the oleoresin preparations are selection of suitable raw material, grinding to the optimum particle-size for extraction, choice of solvent, type of extraction, miscella distillation, and blending.

K. Solvent Extraction

Cardamom seed is ground to coarse powder of particle-size 500–700 μ, which helps in the rupture of flavor cells and is amenable for ready extraction by solvents. Fine grinding should be avoided, which not only results in the loss of volatiles, but also, creates problems during extraction, like slow percolation of the solvent, channeling and engagement of the extractor for longer periods. The powdered spice is loaded into the extractor, which is also called percolator, and extracted with a suitable solvent. The choice of the solvent can be from among acetone, alcohol, methanol, ethyl acetate, ethyl methyl ketone, and so on, or a mixture of these solvents. The selection of the solvent for extraction is a crucial step, and it should be standardized on a small scale at the laboratory level before venturing on to commercial production.

The selected solvent is allowed to percolate through the bed of material by keeping the bottom drain valve open for the escape of air. When the entire material is soaked in solvent, the bottom drain is closed, and sufficient contact time is given for leaching of the solutes into the solvent. After the contact time, the extract, called "miscela" is drained and collected.

For oleroresin production, either soxhlet extraction method (Goldman, 1949) or batch counter current extraction (CCE) is industrially practiced (Nambudiri *et al.*, 1970). The concentrated miscella obtained from each extractor is carefully collected and distilled to obtain the finished product. Most of the solvent (about 90–95%) present in the miscella is recovered by normal atmospheric distillation, while the remaining solvent is taken off by distillation under reduced pressure. Great care should be exercised during distillation to minimize heat damage to the product. After completion of solvent stripping, the product, while hot, is discharged from the bottom still and stored in suitable containers. It has been observed that in a 100 kg batch extraction, the retention of solvent in the spent material is of the order of

60–70 kg and about 95% of this quantity is recovered during the desolventization process. The spent meal after the recovery of solvent is discharged from the bottom side vent of the extractor and dried. Spent meal contains starch, fiber, carbohydrate, protein, and so on and finds application in animal feed composition. It can also be used as a broiler feed and as a source of manure for crops. Cardamom spent meal has been used in the manufacture of scented sticks, used in most Indian (Hindu) homes and temples for worship, known locally as "Agarbathi" (Suresh, 1987). Quality and yield of cardamom oleoresin depends upon the raw material variety, the solvent used and the method of extraction. By using hydrocarbon solvents, oleoresin having 10–20% fixed oil has been obtained while with a polar solvent like alcohol, a fat-free product is obtained (Naves, 1974). Oleoresins containing 54–67% volatile oil have been obtained by Salzer (1975), wherein the fixed oil content varied according to the extracting solvent. The color of the product varies from brown to greenish brown. Kasturi and Iyer (1955) extracted cardamom seeds from which volatile oil is already distilled, using carbon tetrachloride as solvent and got 4% yield of fixed oil. The fixed oil on analysis was found to contain 62.6% oleic acid, 18.3% stearic acid, 8.4% palmitic acid, 10.5% linoleic acid, and 0.3% of caprylic and caproic acids. Miyazawa and Kameoka (1975) and Marsh *et al.* (1977) found palmitic (28–38%), oleic (43–44%), and linoleic (2–16%) acids as the major fatty acids present in the fatty oil. The Central Food Technological Research Institute (CFTRI) in Mysore, Karnataka State, has developed analytical processes for the production of cardamom oil, spice oleoresins and encapsulated spice flavors, which have been commercially exploited by companies involved in spice trade.

A company in the United Kingdom has claimed to have produced good quality cardamom oil by extracting seeds with a hydrofluro solvent having a boiling point of about –26°C. During extraction damages due to heat or oxygen or high pH is eliminated (Anon, 1996).

1. Super Critical Carbon Dioxide Extraction of Cardamom

Use of liquid and supercritical carbon dioxide as a solvent for flavor extraction from plant materials has been a subject of intense study (Schultz and Randall, 1970). Three decades back Shultz *et al.* (1967) used carbon dioxide for the extraction of spices like cardamom, clove, nutmeg, coriander, and celery. The use of carbon dioxide for flavor extraction has several advantages over the traditional methods using other solvents.

The cheap and abundantly available carbon dioxide, which is also noninflammable, nontoxic, and noncorrosive as a solvent has merits. It has been widely accepted as a permitted safe solvent for flavor extraction and does not leave any residue of its own. It behaves either as a polar or nonpolar solvent depending on pressure and temperature employed. It is liquid below its critical

point (31.2°C, 7.38 mPa pressure) above its critical point it is safe. Under normal conditions, density of carbon dioxide is less than 100 g $liter^{-1}$, while under super critical conditions its density varies between 200 and 900 g $liter^{-1}$. Naik and Maheswari (1988) extracted cardamom using liquid carbon dioxide (20°C, 55–58 bar pressure) and using a modified high-pressure soxhlet apparatus. They obtained 9.4% yield in 2.5-h extraction period, while with steam distillation in 5-h extraction period only 9% yield was obtained. The gas–liquid chromatography (GLC) and thin-layer chromatography (TLC) analysis of the extracts showed that liquid carbon dioxide extract contained slightly higher amounts of cineole, terpinyl acetate, geraniol, and α-terpineol (35.72%, 24.87%, 4.53%, and 11.06%, respectively) when compared to steam distilled oil where the corresponding values were 30.25%, 22.05%, 4.22%, and 7.88%. Extraction of cardamom under different conditions of pressure, temperature, contact time, and moisture content did not have much influence on the yield and quality of the product. However, the extraction of nonvolatiles and chlorophyll content increased with the increase in pressure and time. The carbon dioxide extracted cardamom oil although has a better quality when freshly extracted lost its fine aroma during the 90 days of storage. Quality deterioration of the commercial steam distilled oil was comparatively less under similar conditions (Gopalakrishnan, 1994). Table XLIV details the quality of cardamom extracts by different methods of extraction.

Table XLIV
Quality of Cardamom Extracts by Different Methods of Extraction

Parameter	SCF	Hexane extract	Clevenger distilled oil
Yield (%)	7.7	6.2	8.3
Nonvolatile matter (%)	4.6	22.5	–
Color	Pale green	Pale green	Colorless
Aroma	Superior, close to fresh cardamom	Residual solvent note, fresh aroma absent	Varied due to artifact formation, and absence of nonvolatiles
Major components 1,8-cineole	29.7	16.6	31.2
α-Terpenyl acetate	37.0	57.3	35.5
α-Terpeneol	4.6	5.0	2.4
Linalool	2.6	2.3	3.8
Sabinene	4.1	2.2	3.4
β-Pinene	2.8	1.7	2.8
D-Limonene	2.4	2.2	3.3
Linalyl acetate	1.6	1.6	2.1

2. Encapsulated Cardamom Flavor

Encapsulation is a technique in which the flavorant is covered by a suitable material thereby protecting the flavor from exposure to the environment. In this method the liquid aroma concentrate is converted to a solid stable powder from having good shelf life. It is reported that some volatile liquid flavors are retained in microcapsules for periods upto 2 years (Bakan, 1973). The flavor protecting material is called "wall material" or "encapsulating material," and is generally either gum or acacia or a starch derivative such as maltodextrin. The actual flavorant, which is to be encapsulated, is called "core" material. The selected wall material should be food grade and an effective film former should stabilize the emulsified flavor in the process of encapsulation. The encapsulated product is spherical and miniature in size ranging from submicron to several millimeters (Bakan, 1978). When the particle-size of the capsules is less than 500 μ, they are called microcapsules (Anandaraman and Reineccius, 1980).

There are different methods of encapsulation of which spray drying is the most widely used method in the case of cardamom. Encapsulation is also done in the case of black pepper (Raghavan *et al.*, 1990; Sankarikutty *et al.*, 1988). In addition to spray drying method, there are others, such as phase separation, adsorption, molten extrusion, spray cooling or chilling, inclusion complex formation, and so on. In the case of spray drying, the most popular method, the basic steps involved are: (1) preparation of the emulsion, (2) homogenization of the emulsion with the flavorant, and (3) atomization of the mass into the drying chamber. Raghavan *et al.* (1990) have carried out spray drying of cardamom oil using a small spray drier (Bower Engineering, NJ, USA), as well as a pilot spray drier (Anhydro). Up to 7.2 kg yield of the dried product having 4% moisture and 8.5% volatile oil has been obtained. After several trial batches, the optimum oil to encapsulant ratio was found to be 1.4, which very much agrees with the investigations of Sankarikutty *et al.* (1988). These authors have used hot water (50–60°C) in their experiments to aid dispersion of the gum. After mixing cardamom oil and emulsification the globule size was 2 μ. The material was spray dried at an inlet air temperature of 155 ± 5°C and exit air of 100 ± 5°C. For detailed information on the technique, refer Sankarikutty *et al.* (1988). Under ideal conditions, the encapsulated powder should not have any flavor. However, in practice, it has been found that the product has mild odor due to some amount of flavor left unencapsulated and also due to rupture of a few capsules. Attempts have been made to remove surface flavor by washing the particles with hexane (Omanakutty and Mathew, 1985). About 1–2% oil was found on the spray-dried flavors made using different encapsulations.

Gas chromatographic examination of the cardamom oils obtained from the emulsion and their spray dried product showed a similar pattern when compared to the original oil. However, the oil derived from the spray-dried encapsulated product showed a slight decrease in the cineole content (44%) and increase in terpinyl acetate content (38.9%), while the corresponding values in the oil obtained from emulsion were 47.4% and 34.8% (Raghavan *et al.*, 1990; Sankarikutty *et al.*, 1988). Property-wise cineole is more volatile and has lower molecular weight than terpinyl acetate. Stability of the encapsulated cardamom oil product was found to be satisfactory when stored in airtight glass containers at room temperature. The moisture pick up was negligible, and there was only 5% loss of volatile oil during the 2 years of storage period (Raghavan *et al.*, 1990).

The following are the advantages of spray-dried encapsulated cardamom flavors: (1) they are nonvolatile, dry and free-flowing; (2) can be readily incorporated into food mixes to obtain uniform flavor effect; and (3) flavor stability is good over longer storage periods even at higher temperatures, and in aqueous system the capsules break and the flavor is released.

L. Large Cardamom (Nepal Cardamom)

Another type of cardamom of commercial importance is the Sikkim or Nepal large cardamom almost equal to the small cardamom produced in the southern states of India. Thailand, Indonesia, and Laos also produce large cardamom to a limited extent. Large cardamom is used as a flavoring agent in curry powders, sweet dishes, cakes, and for masticatory and medicinal purposes. Physicochemical studies on five cultivars of large cardamom, namely, *Ramsey*, *Golsey*, *Sawney*, *Ramla*, and *Madhusey* have been carried out (Pura Naik, 1996). The studies revealed that percentage husk varied between 27% and 31.5% and seeds 68.2–72.0%. Volatile oil content in seeds ranged from 2.7 to 3.6%. Large cardamom contains less volatile oil than small cardamom and is more camphoraceous and harsh in aroma with a flat cineole color. The oil is rich in 1,8-cineole and devoid of α-terpinyl acetate (Govindarajan *et al.*, 1982b). The chemical composition of the large cardamom oil is well documented (Lawrence, 1970). Products like volatile oil, oleroresin, encapsulated flavor, and so on, can be produced from large cardamom also using the processing methods described for cardamom. Products, such as volatile oil, oleoresin, encapsulated flavor, and so on, can be produced from large cardamom also using the processing methods described for cardamom.

M. Other Products

A number of products having cardamom as the major flavorant can be prepared. Some of these products with commercial value are given below (Raghavan *et al.*, 1991b).

1. *Sugar cardamom mix*: It is a blend of sugar powder with encapsulated cardamom flavor along with sunset yellow colorant and may contain tricalcium phosphate as anticaking agent. This finds application in culinary sweets, flavoring of milk and milk products. Incorporation of the above mix with malted *ragi* (finger millet, *Eleusine coracana*, a popular food milltet in the State of Karnataka) flour makes a good *ragi* beverage, which is very nutritious.
2. *Cardamom flavored cola beverage*: This is an amber-colored sparkling carbonated beverage containing sugar, caramel, acid, and flavors. A market survey on this product was very encouraging and the product was quite acceptable to the consumers.
3. *Cardamom flavored "Flan"*: This product is made from milk, sugar, starch with added color, flavor and gelling agents. It tastes like custard dairy dessert. The formula for its preparation has been standardized by the CFTRI in Mysore, Karnataka State.
4. *Cardamom chocolate*: Cardamom-flavored milk chocolate is prepared by using cocoa mass with butter, sugar powder, milk powder, encapsulated cardamom flavor, and emulsifiers. The resultant product has good consumer acceptability.
5. *Cardamom Plus*: In West German market "Pepper Plus" has found favor with consumers. This product is prepared by fortifying black pepper powder with encapsulated pepper flavor. The advantage of this blend is its rich naturalness with high-flavor strength. On similar lines, "Cardamom Plus" can be prepared by mixing freshly ground cardamom with encapsulated cardamom flavor. In the place of cardamom powder, cardamom residue (subsequent to oil distillation), which contains fixed flavors, and resinous mass, which can only be removed by solvent extraction, can be used. Spent residue is a valuable source for making "Cardamom Plus" preparation.
6. *Cardamom tincture*: This is prepared by extraction of crushed cardamom seeds along with other spices like caraway and cinnamon, and cochineal using 60% alcohol as solvent. Five percent glycerin is added to the extract which is used as a carminative mixture (British Pharmacopoeia, 1980).
7. *Cardamom coffee and tea*: The cardamom flavor is very compatible with coffee and tea. The major use of cardamom in the Middle East countries is as an additive to coffee. This cardamom is called "Gahwa" and it is a traditional drink with Arabs of the Gulf region (Survey of India's Export Potential of Spices, 1968). Encapsulated cardamom flavor is very handy and useful while making "Gahwa" coffee. The flavor is incorporated into

roast and ground coffee, which on brewing imparts a predominantly cardamom-flavored extract. This can also be consumed as black coffee, with or without milk, as in Europe and North America. Similarly, cardamom tea is available in the market in which cardamom powder is mixed with tea powder. Like cardamom coffee, cardamom tea can be conveniently made using encapsulated cardamom flavor, which has a long shelf life.

N. Conclusions

Cardamom flavor finds application in different items, such as processed foods, beverages, confectionery, health foods, medicines, perfumery, and cosmetics. Cardamom products, such as essential oil, oleoresin, and encapsulated flavor, may find good potential in food and nonfood industries because of advantages such as standardized flavor strength, good shelf life, hygienic quality, ease of handling, and stabilized flavor. However, the increase in consumer demand for processed cardamom products is related to the increase in population and the spread of new markets. Both research and marketing are crucial in creating new forms of value-added products of cardamom and also exploration of new market avenues. It is also important for the cardamom-producing countries to create and sustain internal demand for cardamom-based by-products.

X. THE ECONOMY OF CARDAMOM PRODUCTION

Cardamom is an important spice commodity of international significance since the Greek and Roman times. Until 1979–1980, India was the largest producer of cardamom and dominated its international trade earning valuable hard currency for the nation. More than 90% of international trade, both in small and large cardamom, originated in India. However, during the past two decades, Indian cardamom faces a serious threat in international market from Guatemala, which has steadily encroached into India's share of world trade in cardamom. Guatemala, with an average annual production of more than 13,000 metric tons has emerged as the top producer and exporter in the world and India has been relegated to the second position. Cost of cardamom production in India is relatively higher compared to that in Guatemala, mainly on account of poor yield and low productivity. India's highest productivity level in the years of a good crop is 300% lesser than that of the yield in Guatemala. Senility and poor unselected varieties, prolonged drought and overdependence on monsoon, predominance of small holdings, problems of land tenure, inefficient and inadequate attention to management, both in

production and protection practices, faulty postharvest practices, and so on, are some of the important reasons attributed to poor yield (Anon, 1996). The situation warrants a critical evaluation of the above-mentioned limiting factors. To make cardamom production competitive, the first step is an in-depth analysis of the economics of production, marketing, and other aspects affecting cardamom economy of India. In this chapter an attempt is made to analyze the above-mentioned aspects in a holistic manner.

The following table (Table XLV) depicts the production of cardamom during the past quarter century.

India and Guatemala are the major producers and players in the world economy of cardamom. Other small producers are Tanzania, Sri Lanka, PNG, Honduras, Costa Rica, El Salvador, Thailand, and Vietnam. India accounted for nearly 65% of the world production in the early 1970s but by 1997–1998 it had come down to 28%. Guatemala, on the other hand, stepped up its production from the middle of the 1960s contributing only 21.5% of world production in the 1970s, but now its share is 65% of the world production. Unlike India, Guatemala has negligible local demand and all the cardamom produced is exported. Using the "Law of comparative advantage" in cardamom production, Guatemala could increase its share in the world market from 30 to over 90% in the recent past and has already captured the traditional markets of cardamom. In India, the weak infrastructure support, insufficient credit and marketing facilities in the cardamom belt have adversely affected the prospects for cardamom. A vicious cycle of "low price-low production–high price-high production" came into operation. In 1982–1983, there was a steep fall in production which resulted in the

Table XLV
Cardamom Production in the Major Cardamom-Producing Countries of the World

	Per cent share in total world production (mt)			
Period	India	Guatemala	Others	World production (mt)
1970/1971–1974/1975	65.4	21.5	13.1	4678
1975/1976–1979/1980	53.7	34.5	11.8	6628
1980/1981	42.9	48.8	8.3	10,250
1984/1985	31.9	60.3	7.8	12,220
1985/1986–1989/1990	26.5	67.5	6.0	14,392
1990/1991–1994/1995	28.4	65.6	6.0	19,470
1995/1996–1997/1998	29.8	64.2	6.0	24,953

Source: Cardamom Statistics, 1984–1985, Government of India, Cardamom Board, Cochin, Kerala State, India.
Spices Statistics, 1991, Government of India, Spices Board, Cochin, Kerala State, India.
Spices Statistics, 1997, Government of India, Spices Board, Cochin, Kerala State, India.
All India final estimate of cardamom—1997/1998, Government of India, Ministry of Agriculture, New Delhi.
Note: Estimated figures (actual figures are not available).

consequent high price in the domestic market. It was at this stage of recession in production and export that the cardamom industry was badly hit by severe drought in 1983–1984, destroying a substantial portion of yielding area, which was gradually made up by replanting/gap filling in the subsequent years. An analysis of the performance of cardamom industry in terms of area under the crop, production, productivity, export, export earnings, prices, and so on, in recent years would be relevant to plan future programs for the revival of the cardamom crop in India. An analysis of the data on area, production, and productivity is given in Table XLVI, the data starting from

Table XLVI
Area, Production, and Productivity in Cardamom

Year	Area (ha)	Growth index	Production (mt)	Growth index	Productivity (kg ha^{-1})	Growth index
1970–1971	91,480	100.00	3170	100.00	34.65	100.00
1971–1972	91,480	100.00	3785	119.40	41.38	119.42
1972–1973	91,480	100.00	2670	84.23	29.19	84.24
1973–1974	91,480	100.00	2780	87.68	30.39	87.71
1974–1975	91,480	100.00	2900	91.48	31.70	91.49
1975–1976	91,480	100.00	3000	94.64	32.79	94.63
1976–1977	91,480	100.00	2400	75.71	26.24	75.73
1977–1978	91,480	100.00	3900	123.02	42.63	123.03
1978–1979	92,760	101.40	4000	126.18	43.12	124.44
1979–1980	93,950	102.70	4500	141.96	47.90	135.64
1980–1981	93,950	102.70	4400	138.80	46.83	135.15
1981–1982	93,950	102.70	4100	129.33	43.64	125.95
1982–1983	93,950	102.70	2900	91.48	30.87	89.09
1983–1984	93,950	102.70	1600	50.47	17.03	49.15
1984–1985	100,000	109.31	3900	123.03	39.00	112.55
1985–1986	100,000	109.31	4700	148.26	47.00	135.64
1986–1987	105,000	114.78	3800	119.87	38.00	109.67
1987–1988	105,000	114.78	3200	100.95	30.48	87.96
1988–1989	81,113	88.67	4250	134.07	40.48	116.83
1989–1990	81,113	88.67	3100	97.79	38.22	110.30
1990–1991	81,554	89.15	4750	149.84	58.24	168.08
1991–1992	81,845	89.47	5000	157.73	61.09	176.31
1992–1993	82,392	90.06	4250	134.07	51.58	148.86
1993–1994	82,960	90.69	6600	208.20	79.56	229.61
1994–1995	83,651	91.44	7000	220.82	83.68	241.50
1995–1996	83,800	91.60	7900	249.21	94.27	272.06
1996–1997	72,520	79.27	7290	208.99	100.52	290.10
1997–1998	69,820	76.32	7150	225.55	102.40	295.53
1998–1999	72,135	75.85	7170	226.18	135.00	389.61
1999–2000	72,451	79.20	9290	293.06	173.00	499.28

Source: Data from various publications of "Spices Statistics," Spices Board, Government of India, Cochin, Kerala State, Agricultural Production Statistics, Ministry of Agriculture, Government of India, New Delhi.

1970s as the cut off line, starting when cardamom production made an impact, be it in India or Guatemala, the two major cardamom-producing countries in the world.

A. The Emerging Trends in Cardamom Production

1. Area

Data in Table XLVI can be categorized into three parts as follows: (1) 1970–1971 to 1977–1978—period of no change in area, (2) 1978–1979 to 1988–1989—period of increasing area, and (3) 1989–1990 to 1997–1998—period of decline in area. While the area under the crop remained unchanged during the first period of 8 years, there were year-to-year fluctuations in quantity produced indicating the impact of climate on productivity.

2. Production

A significant feature of cardamom production in India is the cyclical fluctuations in yield. After continuous increase in production and productivity for 2–3 years, a decline sets which continues before the production increases. It is the effect of climate as cardamom is a shade-loving plant. There were cyclical fluctuations during 1973–1976, 1978–1981, and 1985–1987. India's production had been showing a consistent increase from 4250 t in 1992–1993 to 7900 t in 1995–1996, but declined to 7150 t in 1997–1998. But, the rate of decline was not as rapid as in the 1970s and 1980s. This may be due to improvement in productivity, where the use of improved varieties and better producting technology contributed much to the overall enhancement in productivity. After 1997–1998 crop years, there is an increasing trend in production.

3. Productivity

The yield level that was around 34.65 kg ha^{-1} during 1970–1971 did not show much improvement until 1980 end, except an increase up to 48 kg ha^{-1} in 1979–1980. It appears that the yield increase during this period has not contributed to the overall increase in production, the entire increase in production accounted for by the increase in area planted. However, productivity level increased from the 1990 onwards and reached a peak of 102.4 kg ha^{-1} in 1997. The productivity in 1997–1998 is a threefold increase compared to that obtained in 1970–1971. The estimated growth rate in production is more

than 225% over the base year. Record productivity of 173 kg ha^{-1} was achieved in 1999–2000 due to better varieties and improved crop practices (Spices Board, 2000).

4. Growth Estimates

In order to get summary measures of long-term trends in area, production, and productivity of cardamom in India, semilogarithmic equations are estimated. The decadal growth rate showed that there was a positive growth rate of 0.2% and 0.1%, respectively in the 1970s and 1980s. It was –1.9% in the 1990s with regard to area. Production had a positive growth rate in all the three decades, but it was the maximum of 8.3% in the 1990s. The figures for productivity are a matter of major concern, as it has direct bearing on the cost efficiency and profitability of cardamom cultivation. The estimated negative growth rate in area and positive growth rate in production in the 1990s indicates the improvement in productivity, that is, with less area under the crop more of production is achieved.

Table XLVII gives data on state-wise area, production, and productivity. It shows that that the cardamom belt of India is located in the Western Ghats regions of the Kerala State, Karnataka State, and Tamil Nadu. Kerala State accounts for the major share of area and production of cardamom in India, and this has remained more or less unchanged over the last three decades. Karnataka State stands second, followed by Tamil Nadu. Over the years productivity per unit area has gone up both in Kerala State and in Karnataka State, but declined in Tamil Nadu.

5. Production Constraints

The major reasons attributed to low productivity of cardamom in India are:

1. Recurring vagaries of climate, especially drought and absence of irrigation practice.
2. Absence of regular replantation. In the mixed cropping system, as for instance cardamom and coffee, the farmer is contended with the additional income from the companion crop and is not disappointed with the lowering of yields in the main cardamom crop due to aging. Replanting with improved varieties would have led to better yields.
3. Deforestation and resultant changes in the ecological conditions prevailing in the growing area—leading to conversion of cardamom land to other competing crops such as black pepper.

Table XLVII
An Analysis of State-Wise Area, Production, and Productivity of Cardamom in India

Period	Variables	Kerala		Karnataka		Tamil Nadu		India
		Actual	%	Actual	%	Actual	%	%
1970–1971	Area (ha)	55,190	60.33	28,220	30.81	8070	8.81	91,480
	Production (t)	21.30	67.19	805	25.39	235	7.41	3170
	Productivity (kg ha^{-1})	38.59		28.53		29.12		34.65
1980–1981	Area (ha)	56,380	60.01	28,220	30.03	9350	9.95	93,950
	Production (t)	3100	70.45	1000	22.73	300	6.82	4400
	Productivity (kg ha^{-1})	54.98		28.22		32.09		46.83
1990–1991	Area (ha)	43,826	53.74	31,605	38.75	6123	7.51	81,554
	Production (t)	3450	72.63	800	16.84	500	10.53	4750
	Productivity (kg ha^{-1})	78.72		25.31		81.66		58.24
1997–1998	Area (ha)	43,050	61.66	21,410	30.66	5360	7.68	69,820
	Production (t)	5430	75.94	1240	17.34	480	6.71	715
	Productivity (kg ha^{-1})	126.13		57.92		89.55		102.41
1999–2000*	Area (ha)	41,522	57.31	25,882	35.72	5047	6.97	72,451
	Production (t)	6550	70.51	1950	20.99	790	8.50	9290
	Productivity (kg ha^{-1})	213		103		205		173

Source: Spices Statistics (various publications), Government of India, Spices Board, Cochin, Kerala State.
Note: Yield is arrived at by dividing total production by area; (*) midterm estimate.

Table XLVIII
Quinquennial Averages of the Indices of Area, Production, and Productivity of Major Commercial Crops (1960–1961 = 100 base)

Period	Rubber			Coffee			Cardamom			Black Pepper		
	A	P	Y	A	P	Y	A	P	Y	A	P	Y
1960/1961–1964/1965	111	131	117	106	101	95	100	113	113	100	93	93
1965/1966–1969/1970	139	258	185	131	157	126	126	113	91	99	85	86
1970/1971–1974/1975	165	448	270	128	209	163	140	120	84	117	94	80
1975/1976–1979/1980	187	569	304	166	266	159	165	160	97	109	91	84
1980/1981–1984/1985	236	647	274	194	293	151	185	273	146	106	97	91
1985/1986–1989/1990	276	930	336	213	388	182	211	320	150	144	152	105
1990/1991–1994/1995							148	173	167	181	182	101

Source: Radhakrishnan (1993).
Note: A, area (ha); P, production (t); Y, productivity (kg ha^{-1}).

4. Lack of eagerness among planters to adopt high-production technology, although better varieties and practically proven package of practices is available to enhance yield level up to 600 kg ha^{-1}.
5. Problems of pests and diseases.
6. Remote location of plantations.
7. System of land tenure which does not allow long-term planning for improvement by the actual producer who works on the land (Anon, 1996; Cherian, 1977; George, 1976).

a. Comparative Picture of Area and Productivity of Cardamom with Other Plantation Crops. Coffee, black pepper, and arecanut are the other plantation crops raised along with cardamom. A comparative picture is given in Table XLVIII.

6. Cost of Production

Productivity and cost of production play crucial roles in deciding competitiveness of the product in the global market. Compared to India, the cost of production of cardamom in Guatemala is much lower. This is because of first, higher productivity and second, lower wages for labor. Productivity in India was a mere 47 kg ha^{-1} in the 1980s, when it was 91 kg ha^{-1} in Guatemala. Guatemala obtains more than 200 kg ha^{-1} (dry capsules), whereas in India, it is only 120 kg ha^{-1}. This in itself gives Guatemala a cost advantage of more than 255%. Guatemala has an advantage over India from cost of production also. For instance production cost was just about US$1 a kg during the 1980s in Guatemala, while in India it was double (Bossen, 1982).

Consequently, Guatemala has been able to edge out Indian cardamom from world market. The price of cardamom from Guatemala in recent years has been around US$5–7 kg^{-1} lower than that in India and the quality of the produce was quite comparable with that from India. Such advantage helped the exporters from Guatemala to penetrate markets earlier held by India. Advances in cardamom-production technology helped India increase productivity per unit area. The highest yield achieved is 2475 kg ha^{-1} in Idukki district of Kerala State in 1999–2000 by a farmer and other farmers have achieved yields more than 1400 kg ha^{-1} (Korikanthimath, 1992). However, the labor component in the production cost, which accounts for more than 60% during the establishment stage of the plantation, and more than 40% thereafter, in the total cost of production makes Indian cardamom a lot more costlier in the international market. Studies have shown that expenditure on labor has a positive correlation with yield ha^{-1} (Mahabala *et al.*, 1991). The present estimated cost of labor in India varies from Rs 150 (approximately US$4) to Rs 200 (approximately US$5) to produce 1 kg depending on the cropping system followed. Thomas *et al.* (1990) have concluded that low productivity and high cost of production vis-à-vis stiff competition in the international market rendered Indian cardamom less competitive and subsequently unremunerative for the planters. Due to nonavailability of skilled labor for harvest and postharvest handling, including on-farm processing, employment of unskilled laborers resulted in less recovery of 19% only as against the desirable recovery of 25%. Thus, an avoidable postharvest loss of around 6.8% is also responsible for reduction in productivity.

7. Domestic Market Structure and Prices

Cardamom trade in India is a regulated trade. Cardamom Rules (1987 Licensing and Marketing) was introduced to streamline the system of marketing in general and bringing about control in the form of restricting the entry of persons into the different functional categories, namely exporters, dealers, and auctioneers. The declared purpose of such regulation is to ensure a fair price for the product and the timely payment of sale proceeds. Export marketing of cardamom is regulated by the Spices Board (Registration of Exporters) regulation 1989. The Spices Board issues the following certificates or licenses.

1. Cardamom dealer licenses
2. Cardamom auctioneer licenses
3. Certificate of registration as exporter of spices
4. Registration-cum-membership certificates to exporters (RCM).

Market Intelligence Officers have been posted in important marketing/ auction centers to collect reports on crop purchase, sales, movement, and price trends.

8. Price Analysis

Analysis of the structure and behavior of farm prices is of considerable interest in the context of finding ways and means for increasing production and productivity. Prices often act as a guide to indicate the change in production decisions.

Cardamom is a moderately storable export commodity. Long-term storage is not possible as in the case of black pepper. This necessitates market clearance within the crop year, thereby ruling out speculations. Within these limits, the formation of prices in the domestic market takes place in the following manner. Depending upon the length of the summer, severity of drought, premonsoon showers, and the quantum of rainfall during June–July period, well-experienced traders forecast the crop size and its prospects for the forthcoming season. This is aided by the fact that many of the dealers and exporters of the crop are themselves cardamom planters. If the expected production is much lower than the normal production, a significantly higher price than that which ruled the season past, is set at the beginning of the season itself. If, on the other hand, the production is much higher than the normal production, a much lower price is set (Nair *et al.*, 1989).

Export value of cardamom usually depends on its major quality aspect of color. Traders are keen to acquire as much as possible of the output in the peak harvest season as high-quality harvest (with good color) comes in the middle of the season. This is what makes for the peak prices in the peak harvesting season, which in turn, becomes the peak sales period. This period is broadly between September and December. An investigation by Joseph (1985) indicates that the export price leads the domestic price with a lag of about 1 month. But, according to Nair *et al.* (1989), although there is trend synchronization between export prices and auction prices, a month-to-month correspondence does not hold. However, there exists an asymmetry, that a rise in the export price is not always paralleled by a corresponding increase in the domestic price, whereas a fall in the export price is transferred entirely to the domestic price.

The estimated growth equation indicated that while auction prices have registered an average annual growth rate of 6.8%, both the wholesale and export prices increased at the rate of 6.4% during the period from 1971 to 1997–1998.

B. Export Performance of Cardamom

Historically, cardamom began to be cultivated in India as an export crop with little attention to domestic consumption. Until the end of 1960s, the crop was in the sellers market in world trade and India was the leader in production and export. Guatemala stepped up its production from

mid-1960s and began capturing India's international market in the Middle East, where cardamom is a priced spice. In India, export peaked in 1985–1986 at 3272 million tons, representing a growth index of 191.91, where 69.62% of the domestic production was exported and in the 1977–1978, while India could only export 2763 million tons, Guatemala exported 3610 million tons, capturing world's number one position as exporter, edging out India. With further increase in production in Guatemala, India's export has been seriously affected. The lowest export from India at 180 (mt) was in 1989–1990, which was just 5.81% of the total production. Indian export was in proportion to the quantum produced until 1985–1986. Thereafter export remained low with consecutive fall in export during 1986–1987 and 1987–1988. Although the level of production went up, the quantity exported remained low. The gap between production and export started widening and the trend continued. At present, cardamom production in the country is maintained only on local consumption. During this period, there was a heavy export from Guatemala and India was simply edged out from the international market. Even export promotion schemes, such as air freight subsidy to the Middle East, where there was a big market for Indian cardamom, exemption of cess (a levy by the government on export trade) and export assistance of Rs 35 kg^{-1} (about US 85 cents, which according to Indian scale of economy is quite a substantial figure), could not help in enhancing export from India. The trade trends of cardamom in India are that almost all of the production is absorbed by the domestic market. The efforts of Spices Board had a positive effect on domestic consumption. Consequently, the enlarged domestic market could sustain the cardamom industry during the years in which international prices were low. Occasionally, although due to enhanced domestic demand, prices went up above that of international market. Although it is a good sign for the cardamom industry to depend on the domestic market, there is yet another problem involved in it. Since export accounts comparatively only for a portion of the total production, the prices are influenced more by the strong internal demand than by external demand. In the 1990s the highest domestic price paved the way for smuggling cardamom from Guatemala through Nepal into India and an estimated 2000 t came into the country through this manner (Anon, 1998). The smuggling trade continues and this has developed into a big menace where local producers are adversely affected and the government has been unable to check this menace effectively, as, there is always a "hand-in-glove" design in such enterprise.

C. Direction of Indian Export Trade

Until the end of the 1980s, more than 80% of Indian cardamom export was to the Middle East, which accounts for over 50% of world import.

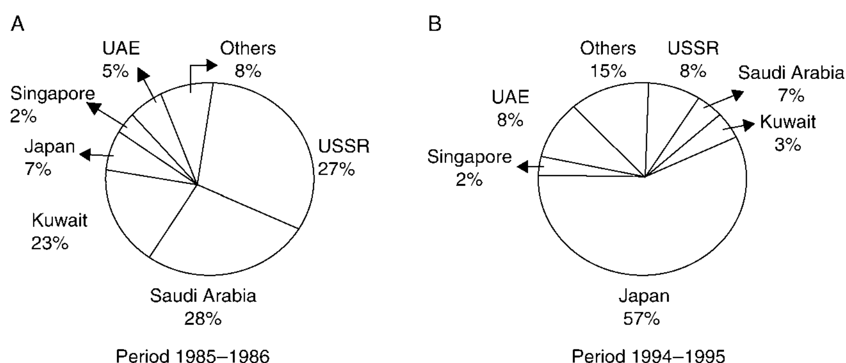


Figure 3 Direction of Indian export of cardamom during 1986–1987 and 1994–1995.

On account of the high degree of quality differentiation of the product in the Middle East market, higher trade in cardamom produced in India was finding a ready market in the Arab world. Demand in this region vastly increased on account of the oil boom which left a lot more cash in the pockets of the Arabs. In recent years, especially in the 1990s, the share of the Middle East market in Indian cardamom export has shrunk, as the oil boom has tapered. The resultant change was from quality consciousness to price sensitivity. Thus, cardamom from Guatemala, although of inferior quality compared to the Indian varieties, priced about US$4–5 kg^{-1} less than that of Indian cardamom, got preference. The result was that India lost its traditional market. India has lost its East European market also after the collapse of the Russian empire. Japan is the only consistent market for Indian cardamom in recent years. In 1995–1996 more than 60% of the total export at 226 mt from India went to Japan. Among the suppliers of cardamom to Japan, India tops the list at 66%, followed by Guatemala and Vietnam. Japan buys the second grade Alleppey Green from India. It is also worth noting that the Japanese buyers maintained consistency in purchase of Indian cardamom even in years of high price. Saudi Arabia and Kuwait are the other markets. Figure 3 gives a pictorial representation of the export performance.

D. India's Competitive Position in the International Cardamom Market

It is the relative price of a product that determines the country's competitive position in the international market. As the main competitor of Indian cardamom is the Guatemalan cardamom, it would be informative to examine

this aspect. The Indian cardamom has always been priced higher than that of Guatemalan cardamom and the former has never been cheap. Productivity of Guatemalan cardamom has been consistently higher than that of India and in 1985–1986 when India's production peaked at 3272 (mt), the corresponding value for Guatemala was 8845.20 (mt) and more than 90% was exported, while in the case of India it was just 70%. This was the peak export for India, while in the case of Guatemala, export had reached 98% in 1990. Both productivity and price advantage contributed to this. But, Guatemalan cardamom is smaller in size and does not have the competitive edge over India's in terms of quality. Yet, it is the price advantage that has helped boost Guatemalan cardamom industry.

E. Demand and Supply Pattern

Cardamom production is influenced by national and international price movements. The response to price changes gets reflected every 5–6 years. While demand is influenced by many factors, including overall economic development of the country, the supply is influenced not merely by economic factors, but also, agroclimatic, biotic, and abiotic stress factors in the growing region. Hence, there are a multitude of factors which are to be considered to forecast the future of cardamom. The type of data available does not permit development of sophisticated forecast models, which would provide a precise picture of cardamom trade. What data India possesses is historic data on area, production, and prices. Based on these informations, suitable models, which would permit a fairly reasonable predictive model, have been identified, and this may only be seen as a preliminary step in the development of more precise and dependable subsequent models.

F. Model Identification

A variety of statistical techniques, ranging from simple to very sophisticated, are available to forecast international trade and price movements. All of them attempt to capture the statistical distributions in the data provided and presents the future uncertainty quantitatively. In view of the body of data available and its quality, the following three models have been employed.

1. Simple moving average models
2. Exponential smoothing models
3. Box-Jenkins models.

To identify the appropriate model the data have to be first explored.

Exploring the data: The time series data on cardamom for area, production, and prices were plotted to identify their specific characteristics to select an appropriate model. The characteristics observed in the time series data for cardamom can be listed as follows:

1. There is an overall positive trend (i.e., the trend cycle accounted for nearly 80%).
2. Nonseasonal in nature, that is, not consistently high or low and the repetitive annual pattern.
3. The time series is nonsatisfactory in both mean and variance.

To forecast the demand and quantity exported Box-Jenkins model has been used with log transformed data.

The model

Holt's (1957) exponential smoothing model uses a smoothed estimate of the trend as well as the level to produce forecasts. The forecasting equation is:

$$Y(m) = S_t + mT_t \tag{4}$$

The current smoothed level is added to the linearly extended current smoothed trend as the forecast into the indefinite future.

$$S_t = \alpha Y_t + (1 - \alpha/\text{ie}(1 - \alpha))(S_{t-1} + T_{t-1}) \tag{5}$$

$$T_t = \gamma(S_t - S_{t-1}) + (1 - \gamma)T_{t-1} \tag{6}$$

where m = forecast lead time, Y_t = observed value at time t, S_t = smoothed level at end of time t, T_t = smoothed trend at end of time t, γ = smoothing parameter for trend, and α = smoothing parameter for level of series.

Equation (5) shows how the updated value of the smoothed level is computed as the weighted average of new data (first term) and the best estimate of the new level based on old data (second term). In much the same way Eq. (6) combines old and new estimates of the one period change of the level, thus defining the current linear (local) trend.

G. The Forecast

Before embarking on the presentation of figures for likely future developments, it needs to be stressed again, that the present forecast is not an accurate exercise based on systematically collected elaborate data. However, the forecast based on historic data helps us to understand the overall direction in which the supply (area and production) will move and price fluctuates.

Forecast is produced with upper and lower confidence limits. The upper confidence limit is calculated for 97.5% and the lower for 2.5%, that is, the actual should fall inside the confidence band 95% of the time.

H. Demand

The major markets for Indian cardamom are Saudi Arabia, Kuwait, Jordan, United Arab Emirates, Qatar, erstwhile USSR, and Western Europe. Other important importers include West Germany, Pakistan, United Kingdom, Japan, and Iran. The highest consumption of cardamom takes place in the Middle East where it is used in the preparation of their traditional drink "gahwa." According to United Nations Commission on Trade and Development in Agriculture, this market accounts for 80 per cent of the total world consumption. In Europe and Scandinavian countries, cardamom is used to flavor bread and pastries. Cardamom is imported in raw and ground forms for use in food manufacturing and special blends. Among the producing countries, India consumes the largest quantity of cardamom in the world.

There was a sharp increase in world demand in the late 1970s, which has remained more or less stagnant during recent years because of declining purchasing power in the Middle East on account of the slump in the oil boom. Although the market has shifted to a preference for lower quality cardamom supplied by Guatemala, the total quantity imported has remained almost unchanged. With the main deciding factors on consumption, namely population, age and income, on the increase, demand for cardamom in countries like Japan has gone up. Unlike in the past, new uses for cardamom in the food and industrial sectors trigger the accelerated demand in international market. And this is growing almost at the rate of global population growth. The world demand was estimated at about 9000 t in 1985–1986, excluding India's domestic consumption. Keeping this as the base line, the demand potential is projected on the basis of an average growth of 2% per annum, which is proportionate to the growth rate of population. Accordingly, demand for 2000–2001 was estimated at 12,000 t. According to Spices Board (1990), with an estimated annual per capita consumption of 8.5 kg, total requirement in India was estimated at 8700 t in 2000 which is projected to escalate to 10,800 t by 2010 AD. As far as India is concerned, the demand for cardamom is increasing more than the population growth. Trends in domestic consumption indicate a sharp increase. As against 1500 t in 1985–1986, domestic consumption has gone up to more than 6850 t in 1997–1998. If the current trend had continued, world demand (including India's) was expected to touch 15,000 t by the turn of the century. When actual data is not available, deducting the quantity exported from total production gives an approximate

consumption in the domestic market. The growth equation fitted for the consumption trend in India is:

$$\text{In } D_t = 6.7110 + 0.0725T \quad R_2 = 0.815$$

Accordingly, the estimated growth rate is 7.3% per annum. This growth rate in demand is much more than the growth rates in production. Under the circumstances, it is unlikely that India can regain her earlier position as the world's largest producer and exporter because an increasing percentage of production goes for domestic consumption leaving very little for export. Although there is a shift in the consumption pattern in the Middle East countries from high-quality Indian cardamom to cheaper Guatemalan cardamom, there is no reduction in quantity imported. Further, new markets are emerging for cardamom worldwide. While the household consumption sector remains intact, rather increasing along with population increase, the recent developments in the industrial use of cardamom (food and nonfood sectors) are also expected to push up global demand for the commodity. By 2005 end, global demand is projected to be 20,000 mt.

I. Projections of Supply

Projections on Indian cardamom, for which a model was developed, for area and production are diagrammatically represented by Figs. 4 and 5. These figures present both the historic and fitted values along with values forecast beyond 1997. Both area and production are expected to grow slowly in the immediate future. The growth in production is expected to be more pronounced than the growth in area, indicating the improvement in yield per unit area. As per the cyclical movements discussed earlier, after the peak achieved in 1995–1996, the 3-year period of decline is already over, and it is the turn of increasing trend to reach the next peak in the cycle. As per forecast value, in the early part of the twenty-first century (2000–2001) the expected production level will be between 8000 and 10,000 t; and the area expansion is expected to touch 90,000 ha during the same period. The improvement in internal and international price will catalyze the supply position to jump in the usual fashion discussed earlier.

The forecast and actual price movement from 1990 onwards is given in Fig. 6. Since the forecast production is insufficient to create sufficient export surplus, and the reports of declining production in Guatemala is already reflected in the form of less supply to the world market by that country during 1998–1999 crop year, the repercussions will be favorable to Indian cardamom producers in the form of increased price. The prevailing higher market price is expected to continue in the near future and there is also a

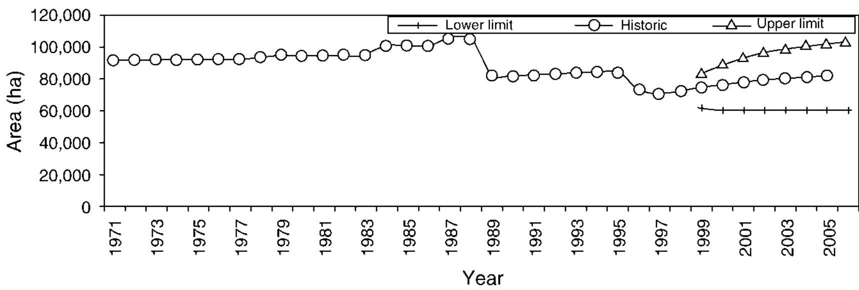


Figure 4 Trend in area under cardamom in India.

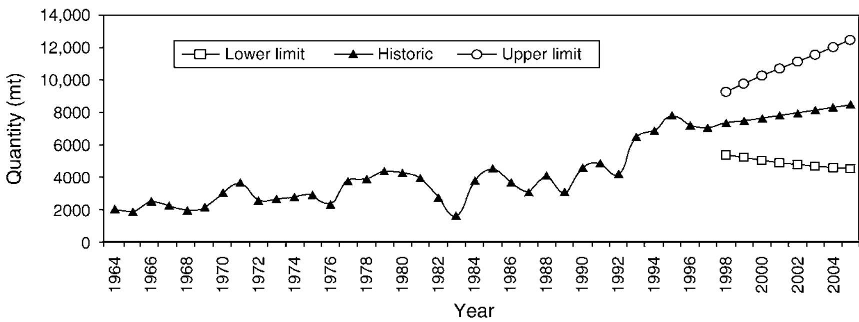


Figure 5 Production trend and forest for cardamom in India.

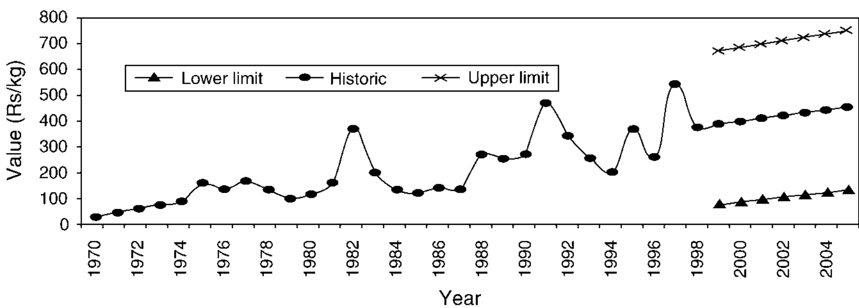


Figure 6 Trend in domestic price of cardamom in India.

possibility for the price to rise to cross the Rs 1000 kg^{-1} (US$23 approximately) mark before declining as per the usual cyclical fluctuations. Availability of less exportable surplus will have direct effect on the export. The forecast standard scenario indicates that the trend prevailing during the last 5 years will continue for the coming 5 years, meaning the export will remain below the 300 t mark. However, the actual estimated export is expected to lie between the upper confidence limit of 97.5% and the actual forecast.

J. Conclusions

Following are the main findings of this chapter.

1. Supply of cardamom is increasing at a fast rate to meet the increasing world demand. Much of the increased supply is from Guatemala. India, while consuming more than half of the total world production, contributes hardly 2% to the world market.
2. While the increase in production during the 1980s was mainly due to the increase in area, during the 1990s the increase in production is due to improvement in productivity. However, the yield gap that exists between the potential productivity level and average achieved level of productivity in the country indicates the possibility of improving yield level considerably.
3. On the export front, India has lost most of its traditional markets to Guatemala because of the price advantage in the case of the latter. Guatemala derives its price competitiveness mainly from low production cost and high productivity per unit area.
4. In the changed scenario, Japan is the steady and reliable market for Indian cardamom. Due to the decline in oil boom and consequent fall in purchasing power of the Gulf market, its preference has changed from quality of the Indian cardamom variety to the price advantage of the Guatemalan cardamom variety.
5. There is a definite pattern of cyclical fluctuation in prices mainly due to the producers' response to price by new as well as replanting, which will start yielding after a certain time lag. Thus, the cyclical fluctuations in prices have an implicit bearing on the condition of supply through farmers' response. The forecast future indicates that there will be a steady increase in supply (production and yield) and the price scenario is expected to either move up from the present level or remain the same as of now. The future scenario, however, can drastically change as a result of innovative product development, diversification of some entirely new application if discovered for cardamom or its products. Imaginative product development programes have to be initiated to boost consumption pattern.

Attractive formulations backed up by catchy advertisements can do wonders in this field.

XI. PHARMACOLOGICAL PROPERTIES OF CARDAMOM

Spices and herbs used in food seasoning often have a mild, broad spectrum of antimicrobial activity. Many crude drugs are used medicinally because of their volatile oil content or other chemical constituents which possess biological activities. Cardamom is very popular as a spice and food additive because of its delicious flavor. The constituents of its volatile oil are responsible for the flavor and fragrance. It also possesses carminative, stomachic, and antimicrobial actions. These biological activities bring about many advantages to the seasoned and prepared foods. Apart from this, cardamom finds application in the indigenous systems of medicine.

A. Pharmacological Properties

In the ancient Indian systems of medicine *Ayurveda* and *Siddha*, cardamom finds application as a component of several therapeutic formulations. *Charakasamhita*, the ancient Indian medical text, describes the use of cardamom as an antiodote to food poisoning. This forms a constituent of Brahmi rasayana which is used as a treatment for inflammations. Cardamom is also used as a component of many balms, ointments, and therapeutic oils used to treat cramps, rheumatic pain, inflammations, and so on. In Ayurvedic texts, the properties of cardamom seeds are described as aromatic, acrid, sweet, cooling, stimulant, carminative, diuretic, cardiotonic, and expectorant. Cardamom is used as an ingredient in preparations used for the treatment of asthma, bronchitis, hemorrhoids, renal and vesicle calculi, cardiac disorders, anorexia, dyspepsia, gastropathy, debility, and vitiated conditions of *vata* (arithmetic pain in knees and joints). But, no pharmacological investigations were carried out to validate the above properties. An aqueous extract of seeds is given to nursing mothers to treat ringworm infection of the children (Aloskar *et al.*, 1992). Roasted seeds are boiled with betel leaves and the extract is used to treat indigestion and worm infection. However, such uses of cardamom in the indigenous system of medicine have not been evaluated pharmacologically.

B. Carminative Action

Both the cardamom seeds and their oil have carminative action. Tincture cardamom is used in many medicinal preparations, which are used as carminative, stomachic, and to relieve colic pain (British Pharmacopoeia, 1993). Tincture cardamom and compound tincture of cardamom are included as official preparations in the British Pharmaceutical Codex 1963, British Pharmacopoeia 1993 and in the Chinese, Hungarian, and Japanese Pharmacopoeia as well. Martindale (1996) in The Extra Pharmacopoeia also describes preparations of cardamom fruits, cardamom oil, and cineole, the major constituent of cardamom oil, as carminative and flavoring agent. Cineole has been used as a counterirritant in ointments and in dentrifices. It has also been used in nasal preparations. Jain *et al.* (1994) have shown that cardamom essential oil containing preparations, such as Brahmi rasayana, suppresses castor oil induced diarrhea in experimental rats. This points to its possible beneficial use in humans as well.

C. Antimicrobial Activity

The terpenoid constituents are responsible for the antifungal and antibacterial effects. Mishra and Dubey (1990) and Mishra *et al.* (1991) studied the effect of cardamom on *Aspergillus flavus*, the fungus which produces the deadly aflatoxin B1. Mycostatic activity was observed at 400 ppm level. This was found to be as potent as synthetic antifungals commonly used (Hirasa and Takemasa, 1998). The flavor components also showed antibacterial effects against several food-borne microorganisms (Kubo *et al.*, 1991). Another study proved that the growth of *Morgenella morganii* was moderately inhibited by the application of cardamom oil or powder (Shakila *et al.*, 1996). This organism is a potent histamine-producing bacterium growing on stored fish. The minimum inhibitory concentration (MIC percent) of cardamom extracts for bacteria and fungi in comparison with a few other common spices are give n the following table (Tables XLIX and L).

D. Anticarcinogenetic Activity

Banerjee *et al.* (1994) have found that cardamom oil enhances glutathione transferase enzyme and acid-soluble sulfhydril activities. These enzymes mediate the oxidation and detoxification of xenobiotics. Cardamom oil was fed to gavage at 10 μl day^{-1} for 14 days and hepatic microsomal enzymes were measured. GST and acid-soluble sulfhydril were found to be significantly elevated (at a high statistical confidence limit of $p = 0.001$).

Table XLIX
Minimum Inhibitory Concentration (%) of Cardamom in Comparison to Other Spice Extracts

Material	pH	BS	Sa	Ec	St	Sm	Pa	Pv	Pm
Cardamom	7	2.0	2.0	<4	<4	<4	<4	<4	<4
	5	0.1	0.5	<4	<4	<4	<4	<4	<4
Cinnamon	7	4.0	2.0	4	4	4	4	2	4
	5	0.5	2.0	4	4	4	4	1	2
Clove	7	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0
	5	0.5	2.0	1.0	1.0	1.0	1.0	0.5	0.5
Mace	7	0.2	0.05	<4	<4	<4	<4	<4	<4
	5	0.1	0.5	<4	<4	<4	<4	<4	<4

Source: Hirasa and Takemasa (1998).
Note: BS, *Bacillus subtilis*; Sa, *Staphylococus aureus*; Ec, *Escherichia coli*; St, *Salmonella typhimurium*; Sm, *Salmonella marcescens*; Pa, *Psudomonas aeruginosa*; Pv, *Proteus vulgaris*; Pm, *Proteus morganii*.

Table L
Minimum Inhibitory Concentration (%) for Some Fungi

Material	Sc	Cp	Ck	P sp.	Ao
Cardamom	4.0	4.0	<4	<4	<4
Cinnamon	1.0	1.0	1.0	1.0	1.0
Clove	0.5	0.5	0.5	0.5	0.5
Mace	<4	<4	<4	<4	<4

Source: Hirasa and Takemasa (1998).
Note: Sc, *Saccharomyces cerevisiae*; Cp, *Candida parakrusei*; Ck, *Candida krusei*; P sp., *Penicillium* sp.; Ao, *Aspergillus oryzae*.

Hashim *et al*. (1994) reported that cardamom oil suppresses DNA adduct formation by aflatoxin B1 in a dose-dependent manner. It appeared to be modulated through the action of microsomal enzymes.

E. Anti-Inflammatory Activity

Yamada (1992) reported that cardamom showed potent complement system activating property. Complements represent the humoral arm of natural immunological host-defense mechanism and are essential for survival. Once activated, this kills certain bacteria, protozoa, fungi, and virus as well as cells of higher organism. Thus, complement activation forms a major part of natural defense affording a range of mediators possessing immunoinflamatory potency.

Jain *et al.* (1994) have shown that the drug *Brahmi rasayana* (*an Ayurvedic preparation*) containing cardamom, with cloves and long pepper, exhibited a dose-dependent anti-inflammatory activity in the case of carrageenan-induced rat paw edema. This drug also inhibited nystatin-induced inflammation in rats. Al-Zuhair *et al.* (1996) have shown that cardamom oil when administered at 175 and 280 μl kg^{-1} of body weight inhibited the growth of carrageenan-induced paw edema in rats by 69.2% and 86.4%, respectively. The anti-inflammatory activity of cardamom oil is comparable to that of indomethancin (indometacin). El-Tabir *et al.* (1997) investigated the pharmacological action of cardamom oil on various animal systems, such as the cardiovascular system of rats, nictitating membrane of cats, isolated rabbit jejunum, isolated guinea pig ileum, and the frog sciatic nerve. The essential oil (5–20 μl kg^{-1} IV) decreased the arterial blood pressure in rats and heart rate in a dose-dependent manner. The effects are antagonistic to the treatment with cyproheptadine (1 mg kg^{-1}) for 5 min. Atropine was also antagonistic to the cardamom-induced bradycardia. The oil was not having any effect on isolated, perfused rat heart, and did not affect electrically induced contractions of the cat nictitating membrane. At concentrations of less than 0.08 μl ml^{-1} the oil-induced contractions of the jejunum; but larger doses relaxed it. Larger dose of the oil was antagonistic to the action of acetylcholine, nicotine, and barium chloride on the rabbit jejunum. The oil at concentrations of 0.01–0.04 μl $liter^{-1}$ induced contractions of the isolated guinea pig ileum; this effect was suppressed by atropine and cyproheptadine. Exposure of frog sciatic nerve to 0.2–0.4 μl $liter^{-1}$ cardamom oil suppressed the frog limb withdrawal reflex, exhibiting a local anesthetic effect (El-Tabir *et al.*, 1997). Al-Zuhair *et al.* (1996) have shown that cardamom oil also exhibited analgesic properties and inhibited spontaneous and acetylcholine-induced movements of rabbit intestine *in vitro* in a dose-dependent manner.

F. Other Pharmacological Studies

From these pharmacological studies the beneficial effects of cardamom, and its oil were established. It is not a mere flavoring agent. It imparts carminative, fungicidal, and bactericidal effects. It activates the complement system thereby the immunobiological defense mechanism of the human body is enhanced. Two other studies reported with extracts of cardamom show another aspect of its therapeutic utility. For instance, extracts of cardamom enhance the percutaneous absorption of medicament. Yamahara *et al.* (1989) studied the dermal penetration of prednisolone using mouse skin model and reported that terpineol and acetylterpineol are the active constituents of cardamom extract, which facilitate the absorption. Huang *et al.* (1993) used rabbit skin model and *in vitro* and *in vivo* studies were conducted.

They observed that the extract of cardamom enhanced the penetration into the skin both *in vivo* and *in vitro* situations. Hence, addition of cardamom extract or terpineol or its acetate in balms and ointments enhances the absorption of medicament through the skin. Terpineol and bornyl acetate exhibits disinfectant and solvent properties and hence used with other volatiles for cough and respiratory disorders. Cineole is an ingredient along with other volatile substances for the treatment of renal and biliary calculi (Martindale, 1996).

Yaw Bin *et al.* (1999) also investigated the effect of cardamom extract on transdermal delivery of indometacin. The permeation of indometacin was significantly enhanced after pretreatment with cardamom oil both *in vitro* (rat, rabbit, and human skin) and *in vivo* (rabbit) studies. The indometacin flux decreased as the length of the pretreatment increased. Both natural cardamom oil and a cyclic monoterpene mixture composed of the components of the oil showed similar enhancement of indometacin permeation, indicating that cyclic monoterpenes are the predominant components altering the barrier property of stratum corneum. This study also showed that the three minor components of cardamom oil (α-pinene 6.5%, β-pinene 4.8%, and α-terpineol 0.4%) had a synergistic effect with 1,8-cineole (eucalyptol) and D-limonene to enhance the permeation of indometacin.

G. Toxicity

There is no toxicity in the use of cardamom by-products. The main use of cardamom is as a spice, and as a flavorant. When flavor substances are added to food items, no health hazard should arise at the concentrations used, as they are used only in small doses, normally not exceeding 10–20 ppm of the total quantity of the food item. Higher concentrations cannot be used because of the intense odor and taste. Most of the individual components of cardamom oil were studied to assess their toxicological actions on experimental animals. The investigations were conducted under the auspices of international food safety program. In the series of technical Reports by the joint FAO/WHO Expert Committee on Food Additives, cardamom oil and its chemical constituents are excluded from having any toxicological effects. In allopathy use of cardamom is only as a carminative in certain medical formulations.

1. Antioxidant Function

Cardamom exerts only mild antioxidant function and hence is not effective in preventing food spoilage. The antioxidant function of cardamom in comparison with a few selected major spices is given later (Table LI).

Table LI
Antioxidant Activity of Cardamom and a Few Other Selected Spices Against Lard (Con. Added 0.02%)

Spice	Ground spice (*POV, meq kg^{-1})	Petrol ether soluble fraction (POV meq kg^{-1})	Petrol ether insoluble fraction (POV meq kg^{-1})
Cardamom	423.8	711.8	458.6
Black pepper	364.5	31.3	486.5
Cinnamon	324.0	36.4	448.9
Clove	22.6	33.8	12.8
Turmeric	399.3	430.6	293.7
Nutmeg	205.6	31.1	66.7
Ginger	40.9	240.5	35.5

Source: Hirasa and Takemasa (1998).
*POV, peroxide value which is negatively correlated to the antioxidant property.

2. Pharmaceutical Products

Blancow's (1972) Martindale details the following preparations using cardamom.

1. Aromatic cardamom tincture (BPC, tincture cardamom aromatic, carminative tincture): This is prepared in the proportion of 1 part cardamom seed in about 15 parts of strong ginger tincture, alcohol (90%) and oil caraway, cinnamon and clove.
2. Compound cardamom tincture (BP, tincture cardamom compound). This is prepared from cardamom, cochineal and glycerin by percolation with 60% alcohol. Often the tincture is decolorized by alkaloidal salts, bismuth carbonate, calcium ions and sodium bromide
3. Compound cardamom tincture (USNF). Prepared by macerating 2 g of cardamom seed, 2.5 g of cinnamon and 1.2 g of caraway with 5 ml glycerin and diluted with 100 ml alcohol.

H. Other Properties

1. Effect on Stored Product Insect Pests

Huang *et al*. (2000) investigated the contact and fumigant toxicities and antifeedent activity of cardamom oil on two stored product insect pests (*Sitophilus zeamais* and *Trilobium castaneum*). Topical application was employed for contact toxicity studies, and filter paper impregnation was

employed for testing fumigant action. The adults of both insects were equally susceptible to the contact toxicity of the oil at the lethal dose (LD) 50 values of 56 and 52 μg mg^{-1} in the case of the insect pests *Sitophilus zeamais* and *Trilobium cataneum*, respectively. For fumigant toxicity, the adults of the former were more than twice susceptible than the latter at both LD 50 and LD 95. Twelve-day-old larvae of *Trilobium castaneum* were more tolerant than the adults to the contact toxicity of the oil. The susceptibility of the larvae to contact toxicity increased with age. Cardamom oil applied to filter paper at concentrations ranging from 1.04 to 2.34 mg cm^{-2} significantly reduced the hatching of *Trilobium castaneum* eggs and the subsequent survival rate of the larvae. Adult emergence was also drastically reduced by cardamom oil. When applied to rice or wheat, cardamom oil totally suppressed F1 progeny production of both insects at a low concentration of 0.0053 ppm. Feeding deterrence investigations showed that cardamom oil did not have any growth inhibitory or feeding deterrence effects on either adults or larvae of *Tribolium castaneum.* However, the oil significantly reduced all the nutritional indices of the adults of *Sitophilus zeamais* (Huang *et al.*, 2000).

2. Effect of Cardamom on House Dust Mite

It is generally held that 70% of the allergy caused in humans show positive antigenic reaction for house dust mites (*Dermatophagoides farinae* and *Dermatophagoides petronyssinus*). Yuri and Izumi (1994) studied the effect of essential oil of spices on *Dermatophagoides farinae*, and reported that some of the spice essential oils were effective against this mite (Table LII). They used a concentration of 80 μg cm^{-2} on filter papers, and the mortality rate was counted after 24 h. The essential oil of cardamom exerted only low mortality rate.

Antihelminthic activity of spice extracts was studied by Tsuda and Kiuchi (1989) and found that methanol extract of cardamom exhibited antihelminthic effect on dog round worm.

3. Cardamom in Traditional Systems of Medicine

In the ancient Indian systems of medicine, namely *Ayurveda, Siddha*, and *Unani*, cardamom is used as a powerful aromatic stimulant, carminative, stomachic, and diuretic. It also checks nausea and vomiting and is also reported to be a cardiac stimulant. Powdered cardamom seed mixed with ground ginger, cloves, and caraway is helpful in combating digestive ailments. Tincture of cardamom is also made and used chiefly in medicines for

Table LII
Mortality Rate of *Dermatophagoides farinae* Following the Use of Cardamom Essential oil in Comparison with Other Selected Spice Oils

Essentail oil of	Mortality rate (%)
Cardamom	4.7
Clove	97.3
Mace	0.5
Nutmeg	–
White pepper	0.1
Anise	56.5
Garlic	72.8

windiness or as a stomachic. A good nasal application is prepared by using extracts of cardamom, neem, and myrobalan along with animal fat and camphor. Cardamom seeds are chewed to prevent foul breath, indigestion, nausea, and vomiting due to morning sickness in pregnancy, excessive watering in mouth (pyrosis), and so on; gargling with infusion of cardamom and cinnamon cures pharyngitis, sore throat, and hoarseness of voice during infective influenza. Its daily gargle protects from the influenza infection (Pruthy, 1979).

Powdered cardamom seeds boiled in water with tea powder imparts a pleasant aroma to tea, which is a highly popular practice in the Arab world, and can be used as a medicine for scanty urination, diarrhea, dysentery, palpitation of heart, exhaustion due to excessive work, depression, and so on (Singh and Singh, 1996). Eating cardamom capsule daily with a tablespoon of honey improves eyesight, strengthens nervous system, and keeps one healthy. It is believed by some people that excessive use of cardamom causes impotency.

One of the main properties of cardamom is its effect on dermatological disorders. Medicated cardamom oil and cardamom powder can retard the spread of different hypopigmentation on the face (Nair and Unnikrishnan, 1997). Cardamom powder is a safe emetic that can be used in bronchial asthma patients when excess of sputum is present in the lungs. Further it is a very good cough suppressant. Cardamom finds a place in the formulation of lozenges for the management of common cold and associated symptoms (Nair and Unnikrishnan, 1997). In the form of tincture or powder, cardamom is a frequent adjunct to other stimulants, bitters, and purgatives. A decoction of cardamom with its pericarp mixed with jaggery is a popular home remedy, which relieves giddiness caused by biliousness. A mixture of cardamom seeds, ginger, clove, and caraway in powder form in equal parts is a good stomachic in atonic dyspepsia. A powder made of equal parts of parched cardamom seed, aniseed, and caraway seed is a good digestive.

Cardamom is used in as many as 24 important preparations in *Ayurveda* in the form of decoctions, oils, and powders as well as medicated fermented beverages like *Arishta* and *Aasava* (Sahadevan, 1965a). Cardamom seeds along with saffron (*Crocus sativus*), galengal (*Alpina galanga*), and "nealgor of the corryrium" (Ayurvedic preparation) cure cataract and other eye ailments like tumors in eyelids, fleshy growth, and ophthalmia.

Cardamom fruit is an emmenagogue, the only spice to qualify for this property. Cardamom, cinnamon, tejpatra (*Cinnamomum tamala*), *and iron wood tree* (*Mesua ferrea*) taken together is known as *Chaturjata.* They are used to flavor electuaries to promote their actions (Warrier, 1989). Cardamomm is also a component of medicinal preparation used to cure skin diseases, poisons, cold, and inflammation. Preparations such as *Eladigana* (Ela, cardamom), are a common cure for *vata* (arthritis) and *kapha* (congestion) diseases, poison effects, to enhance complexion, and to cure itching. It is also an ingredient of mixtures to improve digestion, cure vomiting, cough, and so on. Cardamom stimulates diuresis, particularly in the case of snakebite. A group of medicines known as *Ariyaru kashayam* (six grains) for the skin diseases of children contains cardamom.

The Burmese (Myanmar) traditional medicine formulation—O2 (tmf-O2) consists of four basic plant ingredients one of which is cardamom (others being *Anacyclus pyrethrum*, *Glcyrrhiza glabra and Syzygium aromaticum*).

I. Cardamom as a Spice

Cardamom for culinary use: The major use of cardamom worldwide is for culinary purposes in the whole or ground form. In Asian kitchen, cardamom is an important ingredient to prepare a variety of dishes, like spiced rice, vegetables, and meat preparations. Cardamom can add a lingering sparkle to many dishes, both traditional and modern. International trade in cardamom is dependent, however, on the demand created by specialized applications that have evolved in two distinct markets, namely, the Arab market of the Middle East and Scandinavia.

Cardamom provides a warm, comforting feeling, and it is responsible for the unique and exotic flavor of Bedouin coffee. In the Middle East, religious ceremonies, social functions like marriages, etc., and celebrations are incomplete without the use of cardamom and serving the famous Arab coffee, *Gahwa* (cardamom flavored coffee). It is believed by the Arabs that the *Gahwa* cools the body heat in a region where extreme heat is daily feature of life. It is also believed to aid digestion and acts as an aphrodisiac. Cardamom is also used in indigenous Arab cooking. The Arabs have adopted a number of Indian delicacies, especially meat based, and the Arab *Biryani* (a rice based dish with different kinds of meat, principally lamb or chicken meat) is

incomplete without the sprinkling of cardamom capsules. In the Islamic Republic of Iran, cardamom is used in making confectionery, bakery, and meat preparations to add flavor and aroma to the products. Invariably cardamom is found in the spice chest of Indian kitchen. The Indian housewife uses this unique spice in a variety of vegetable and meat dishes including flavoring of sweets and also rice porridge (known locally as *Payasams* in southern India and *Kheer* in northern India).

In European countries and North America, cardamom is used mainly in ground form by food industries as an ingredient in curry powder, some sausage products, fruit cups, green pea soups, curry-flavored soups, spice dishes, rice Danish pastry, buns, breads, rolls, cookies, desserts, coffee cakes, orange salad, jellies, baked apple coffee, honey pickles, pickled herring, canned fish, and to a small extent in flavoring tobacco and cigarettes. Cardamom cola, instant *Gahwa*, carbonated *Gahwa*, biscuits, Spanish pastries, toffees, chewing gum, and so on, are other products where cardamom is an ingredient. Various breakfast foods using encapsulated cardamom oil are new products developed in the recent past using cardamom. It is also used in spiced wine and to flavor custard (by steeping crushed cardamom seeds in hot milk). In general, the Arabs use it in coffee. The Americans use it in baked foods. The Russians add it to pastries, cakes, and confectionery to impart the unique flavor and aroma, while the Japanese use it in curry, ham, and sausage; the Germans use it in curry powders, sausages, and processed meat. The list goes on where the spice is used in countless food items.

In Scandinavia cardamom is widely used in bakery products. The ground cardamom is mixed with flour to add flavor to most baked products and it adds an exotic taste to apple pie (Rosengarten, 1973). In Sweden, cardamom use is most popular with baked foods, where the per capita consumption of such foods is about 60% greater than that in the United States. Ground cardamom is also used to flavor hamburgers and meat loaves.

Indian cardamom is low in fat and high in protein, iron, vitamin B and C (Pruthy, 1993). Table LIII gives the nutritional value of cardamom. In India, it is used as a masticatory and also in flavoring culinary preparations. In several cities of India, especially in the North Indian belt, cardamom is used in the preparation of all kinds of puddings, which are inevitable items in both social functions like marriages and also in religious festivities. It is also used to lace tea, with or without lime, which is a popular and refreshing drink in North India (Philip, 1989). And on many occasions, cardamom seeds are offered to be chew after sumptuous marriage feasts. Also, cardamom flavored hot water is provided in many North Indian hotels. In India, of late, a variety of cardamom-flavored products are being marketed, raging from biscuits to cheese, milk-based drinks, and so on. It is also used to make garlands for special occasions to greet dignitaries both in India and in the Arab world.

Table LIII
Nutritional Composition of Cardamom per 100 g

Ingredients	USDA Handbook 8–21[a]	ASDTA[b]
Water (g)	8.28	8.0
Food energy (Kcal)	311.00	360.0
Protein (g)	10.76	10.0
Fat (g)	6.70	2.9
Carbohydrates (g)	68.47	74.2
Ash (g)	5.78	4.7
Calcium (g)	0.383	0.3
Phosphorus (mg)	178.00	210.0
Sodium (mg)	18.00	10.0
Potassium (mg)	1119.00	1200.0
Iron (mg)	13.97	11.6
Thiamine (mg)	0.198	0.18
Riboflavin (mg)	0.182	0.23
Niacin (mg)	1.102	2.33
Ascorbic acid (mg)	–	ND
Vitamin A activity (RE)	Traces	ND

[a] *Composition of Foods: Spices and Herbs*. USDA Agricultural Handbook, 8–21, January 1977.
[b] The nutritional composition of spices, ASTA Research Committee, February, 1977.
Source: Stobart (1982).
ND, not detected.

1. The Pattern of Suitability of Cardamom

The suitability pattern of cardamom is pictorially depicted in Fig. 7. Cardamom is most suitable in Indian cooking and does not show above average suitability for any other national cuisines. In fact, the use of cardamom is totally lacking in the cuisines of most European and American countries. Hirasa and Takemasa (1998) indicated that cardamom is more useful in meat, milk, and fruit preparations. It is more useful for simmered, baked, fried, deep fried, and pickled food and less suitable for steamed food. The spice is used in the preparation of food mainly for the following purposes

1. Direct flavoring of the dish
2. To mask undesirable flavor and to deodorize
3. To add color to the food
4. To add pungency.

Since a single spice cannot contribute all the qualities mentioned earlier, often a combination of spices is used in the preparation of food. Cardamom is used mainly for its direct effect of imparting flavor.

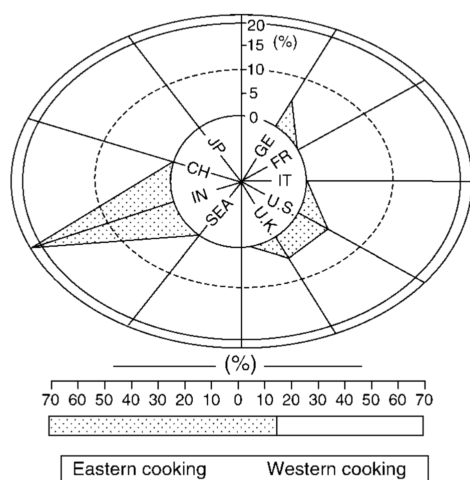


Figure 7 Suitability pattern for cardamom (Source: Hirasa and Takemasa, 1998).

It is used for the same purpose in blended spice mixtures, such as, curry powder, *Garam masala* (a strong mixture of several spices including cardamom to impart aroma and pungency to Indian cuisine), mixed pickles, and so on. Masking undesirable flavor odors is important in the use of spices. According to Weber–Fecher law, the strength of an odor perceived by the strength of smell is proportional to the logarithm of the concentration of the smelled compounds. In other words, the sensational strength perceived by the five senses is proportional to the logarithm of the actual strength of these stimuli. Thus, even if 99% of the total smelled compounds are eliminated chemically, the sensational strength perceived is reduced only by 66% (Hirasa and Takemasa, 1998). Hence, it is more effective and easy to mask the remaining 1% through aromatic spice. Tokita *et al.* (1984) investigated the deodorizing efficiency of various spices. The deodorizing rate (measured by the percent of methyl mercaptan (500 mg) captured by methanol extract of the spice) of cardamom is low (9%) compared to other spices (99% for thyme, 97% for rosemary, 90% for mint, 79% for clove, 30% for black pepper). Ito *et al.* (1962) calculated the deodorizing points for major spices in masking mutton odor. Cardamom showed a deodorizing point of 30, compared to 600 of black pepper, 90 of ginger, 50 of cinnamon, 25 of celery, 23 of garlic, 5 of coriander, 4 of caraway, 3 of clove, 2.5 of thyme, and 0.7 of sage. Thus, cardamom is more effective in masking certain odors than many other spices, although its masking capacity is poor with regard to some other flavors.

Desrosier (1978) investigated the relative flavor intensities (RFI) of various spices and cardamom was found to have an RFI of 125, compared to

200 of turmeric, 260 of curry powder blend, 300 of celery, 400 of cinnamon, 450 of black pepper, 475 of ginger, 600 of clove, 900 of cayenne pepper, and 1000 of fresh red pepper.

2. Spice Blend and *Garam Masala*

Ready to use spice formulations are available in market under many brand names. They are available either as dry powder or as soluble seasonings, which are spice extracts on salt or dextrose carriers. Most common spice blends are curry powders, pickling spice mixes, fish or meat *masala* mixes, and *Garam masala*, and all of them are available under a variety of brand names.

Curry powders are most extensively used in Indian cuisine, and there are virtually hundreds of them in the market for specific need. The basic ingredients in most brands are coriander, cumin, turmeric added for color, and red chilies for pungency. Other spices, such as black pepper, cardamom, cinnamon, and so on, are added to enhance the flavor of the curry powder and as taste enhancers to suite the Indian palate. In many such formulations, cardamom is used to impart specific flavor but only in small quantities. The relative proportion of cardamom in a typical curry powder formulation is given in Table LIV. The US federal specification for curry powder is given in Table LV.

Garam masala is a blend of spices having an approximate composition of the following ingredients.

Cumin seeds—½ oz, cardamom—1/2 oz, black pepper—1/2 oz, cinnamon—1/4 oz, and clove—1/4 oz. Other spices used in the preparation of *Garam masala* add unique tastes for various dishes, but cardamom is the major component. Kalra *et al.* (1991) and Premavalli *et al.* (2000) analyzed the composition of *Garam masala* brands available in the Indian market and found the use of 11 spices (Kalra *et al.*, 1991), while 9–11 spices were found by Premavalli *et al.* (2000). The type of ingredients and the proportions in which they are used is a trade secret. Premavalli *et al.* (2000) found that in all 27 spices were used in the preparation of *Garam masala* of which 5 are common to all brands (coriander, cumin, black pepper, clove, and cardamom). Cardamom imparts a special flavor to the *Garam masala* mix and its use is mainly as a taste and flavor enhancer.

3. Cardamom Oil, Oleoresin, and Soluble Cardamom

Cardamom oil is colorless or pale yellow with an aromatic pungent odor and taste. It is produced in small quantities in some western spice-importing countries, and also in India, Guatemala, and Sri Lanka. The essential oil

Table LIV
Formulations for Typical Curry Powder Blends

Freshly ground spices	US standard formula no. 1[a] (%)	General purpose curry formulas			
		No. 2 (%)	No. 3 (%)	No. 4 (%)	No. 5 (%)
Coriander	32	37	40	35	25
Turmeric, Madras	38	10	10	25	25
Fenugreek	10	0	0	7	5
Cinnamon	7	2	10	0	0
Cumin	5	2	0	15	25
Cardamom	2	4	5	0	5
Ginger, Cochin	3	2	5	5	5
Pepper, white	3	5	15	5	0
Poppy seed	0	35	0	0	0
Clove	0	2	3	0	0
Cayenne pepper	0	1	1	5	0
Bay leaf	0	0	5	0	0
Chilli, hot red pepper	0	0	0	0	5
Allspice	0	0	3	0	0
Mustard seed	0	0	0	3	5
Dried lemon peel	0	0	3	0	0
	100	100	100	100	100

[a]From the US Military Specification Mil-C-35042A, December 30, 1964.
Source: Farrell (1985).
Formula No. 2 is considered a mild curry, formula No. 3 a sweet curry, and formula No. 4 a hot type, formula No. 5 a very hot, pungent Indian style curry more suited for use in the more tropical regions of India.

Table LV
Federal Specification ES-S-631 J for Curry Powder

Ingredient	Limit (%)
Turmeric	37.0–39.0
Coriander	31.0–33.0
Fenugreek	9.0–11.0
Cinnamon	Not < than 7.0
Cumin	Not < than 5.0
Black pepper	Not < than 3.0
Ginger	Not < than 3.0
Cardamom	Not < than 32.0

Source: Tainter and Grenis (1993).

finds its main application in flavoring of processed foods, but it is used also in certain liquid products such as cordials, bitters, and liquors and also, occasionally, in perfumery. Perfumery and cosmetic industries employ the oils of several spices including that of cardamom in the blending of volatile and fixed oils to make dozens of alluring perfumes, far superior in quality than that of the crude scents of the ancients (Bhandari, 1989).

Oleoresin of cardamom is produced in some spice-producing western countries and in India and has similar applications as that of the essential oil in flavoring of processed foods, but is less extensively used. Both the essential oil and oleoresin tend to develop "off flavors" when exposed to air for prolonged periods and their usage is generally confined to meat products and intended for other short shelf-life products such as sausages. Cardamom oil and oleroresins are used mostly as soluble spice, mixed with a carrier such as common salt or dextrose. They are used in processed foods industry. It is easy to use soluble spices, as they are dry, free-flowing powder compared to liquid essential oil or oleoresin. However, much care is needed while replacing ground spice with oil, oleoresin, or soluble spice. Such products often need not represent the freshly ground spice in its richness of flavor due to the loss of some delicate components. Much investigation needs to be done in each of the food system to match oleoresin and oil with that of the ground spice. The replacement ratio for cardamom in comparison to other spices are given in Table LVI.

The Central Food Technological Research Institute (CFTRI), Mysore, Karnataka State, India, has carried out innovative research and development efforts in diversifying cardamom uses to widen the domestic and export markets for cardamom products. Cardamom flavor has been encapsulated using an innovative technology. Encapsulated spices possess unique features like free-flowing nature, uniform flavor strength, and convenience of use. The flavor that is encapsulated is released instantly on contact with water (Pruthy, 1993). Cardamom-cola, a fizzy drink with cardamom flavor, a *flan mix*, an instant dessert mix with cardamom flavor, cardamom tea, cardamom coffee, cardamom milk, dry cardamom powder for soft drinks mix, and instant *Pongal* (a favorite delicacy of Tamil Nadu) mix flavored with cardamom are some other products developed by CFTRI (Pruthy, 1993). Innovative product development programs can help diversification of cardamom use leading to the creation of new dishes and food items.

J. Conclusions

Cardamom is in use from ancient times as a flavoring agent and also as a component in many indigenous medicines of India. Cardamom flavored tea and coffee form part of the daily routine of people in the Middle East.

Table LVI
Replacement Ratios of Cardamom in Comparison to Other Spices

Spice	Replace 1# of ground spice with		Remarks
	# Oil	# Oleoresin	
Allspice	0.020	0.035	
Anise	0.020	0.050	
Basil	0.005	0.050	
Cardamom	0.030	0.015	
Caraway	0.010	0.050	
Celery	0.010	0.100	
Cinnamon	0.025	0.025	Oil use based on volatile oil
Clove	0.140	0.050	Stem, leaf, or bud oil can be used
Coriander	0.003	0.070	
Cumin	0.020	0.040	
Dill seed	0.020	0.050	
Fennel	0.010	0.050	
Ginger	0.015	0.035	
Mace	0.140	0.070	Nutmeg oil should be used
Marjoram	0.008	0.050	
Nutmeg	0.060	0.080	Spice and oil must be from the same origin
Oregano	0.015	0.040	
Black pepper	0.015	0.050	Oil does not provide piperine bite
Rosemary	0.008	0.040	Oleoresin is deflavored for antioxidant preparation
Sage	0.010	0.050	
Savory	0.005	0.065	
Tarragon	0.002	–	

Source: Tainter and Grenis (1993).

Chewing cardamom after a meal is a habit with a large number of people, especially in northern India. It also is used to flavor oral formulations of many medicines, bakery product and milk. Cardamom is unique because of its delicate blend of aroma. The potentialities of this great spice have not been fully exploited. Cardamom is important only in Indian and South Asian cooking but has only minimal influence on continental, American, or Japanese cuisine. Diversification of cardamom-based products with eye-catching advertisements can create fresh demand for this unique spice. The reported property of cardamom extract in enhancing the percutaneous absorption of medicaments can be made use of in the preparation of skin ointments and balms as well as in oral formulations. Innovative technologies are needed to enhance the global demand for cardamom. Product development including novel cardamom-flavored dishes would form an important component of this drive.

XII. A PEEP INTO THE FUTURE OF CARDAMOM

It was in the early 1930s that cardamom, from its original home India, spread to Guatemala. India continued to be the largest producer until the 1980s. The situation has been reversed and it is Guatemala, which is leading in production and export. During the last two decades while Indian cardamom showed fluctuating trends in production and export, Guatemala has forged ahead in production and productivity and also export. For the sake of comparison, the scale of production and export from India and Guatemala are given in Tables LVII and LVIII.

World production of cardamom during 1980–1981 was about 10,250 t and after a decade in 1990–1991 it rose to 16,000 t—a jump by 156%, which further increased to 22,800 t after the next decade in 2000–2001, a further jump by 142%, which peaked at 25,800 during the following 1 year 2001–2002, the highest ever recorded, a further jump by 110%. In other words, during the last two decades of the century past, cardamom production increased by 244%, averaging an increase of more than 12% per annum. India has been the largest exporter until 1980–1981. And the supremacy was challenged by Guatemala, especially during the last decade of the century past. Practically with no domestic demand, the entire quantity produced in Guatemala was exported. By contrast, cardamom finds a ready domestic market in India. Owing to well-developed internal market, domestic prices are high and often higher than international prices and often export from India is not possible because of the comparatively low international price on account of the steady supply position from Guatemala. Table LVIII gives data on export.

Table LVII
Cardamom Production (t) in India and Guatemala

Period	India	Guatemala
1990–1991	4750	11,500
1991–1992	5000	11,120
1992–1993	4250	13,500
1993–1994	6600	13,500
1994–1995	7000	14,200
1995–1996	7900	15,300
1996–1997	6625	17,000
1997–1998	7900	15,000
1998–1999	7170	13,000
1999–2000	9330	10,000
2000–2001	10,480	11,800
2001–2002	11,365	13,500

Source: India, estimates by Spices Board; Guatemala, FAO, Rome, Embassy of India in Mexico.

Table LVIII
Cardamom export (t) from India and Guatemala

Period	India	Guatemala
1990–1991	400	11,114
1991–1992	544	13,163
1992–1993	190	13,000
1993–1994	387	13,000
1994–1995	257	14,000
1995–1996	527	15,000
1996–1997	226	14,500
1997–1998	297	14,500
1998–1999	476	12,000
1999–2000	646	8536
2000–2001	1100	D.N.A

Source: India, DGCI & S, Kolkota/shipping bills/exporters returns. Guatemala: up to 1991–1992 Banco De Guatemala and from 1992 to 1993 estimates based on past trends. D.N.A., data not available.

India and Saudi Arabia are the largest cardamom consumers in the world. Both the countries put together consume more than 50% of total world production. As Indians enjoy self-sufficiency in cardamom, import is not encouraged by the government. Yet, cardamom from Guatemala comes through the Nepal border into India and is posing a great menace to Indian production as this import, although clandestine, is price competitive although the cardamom from Guatemala is of lower quality. The government of India has been unable to check this economic offence. Table LIX gives a comparative picture of cardamom consumption by India and Saudi Arabia.

Saudi Arabia imports its entire requirement from Guatemala. Other important importing countries are: Kuwait, Jordan, Quatar, United Arab Emirates, Japan, Singapore, Russia, United Kingdom, Germany, Scandinavian countries such as Sweden, Norway, Finland, and Denmark. Saudi Arabia is world's highest consumer of cardamom, where it is extensively used in the preparation of the traditional drink *Gawha.* This drink is popular also in Kuwait, Muscat, and Doha. It is reported that *Gawha* normally contains 30% cardamom, and the balance is made up of coffee powder. Often the ratio of cardamom to coffee powder can also vary in the ratio of 60:40 or 50:50. It is the elderly and conservative Arabs in the Middle East who enjoy the *Gawha* (Sahadevan, 1965b). Similarly, cardamom tea is also popular in the Middle East as well as in India (Anon, 1952b). In India, cardamom is consumed not only in households, but also, in industrial units and research institutions. A survey conducted by the Spices Board of India indicates that cardamom finds manifold applications (Anon, 1977a). The main reason for the choice of cardamom is its cool, refreshing aroma

Table LIX
Cardamom Consumption (t) by India and Saudi Arabia

Period	India	Saudi Arabia*
1990	4350	5272
1991	4456	6639
1992	4060	6000
1993	6213	3853
1994	6743	2709
1995	7373	7488
1996	6399	8524
1997	7603	7603
1998	6694	6569
1999	8684	6249
2000	9380	6628

Source: Spices Board of India; UN Statistics: 1990–2000.
Note: Based on import statistics.

with pleasant and sweet taste. The average household consumption of cardamom in India in both urban and rural areas is about 35 kg year^{-1}. The household consumption is estimated to grow at a rate of 3.7% per annum to attain a level 6150 t in the early part of the current century (George and Johan, 1998). Although the total consumption is less, industrial units are the bulk consumers of cardamom in India. Their preparations comprise *Pan masala* (a betel nut, *Areca catachu* based chewing mixture which is very popular in northern India and Pakistan), other *Masala* (explained in earlier sections) products, herbal medicines, tobacco products, biscuits and similar items, and cardamom oil. The demand from the industry was around 2050 t in 2000 at a growth rate of 15% per annum.

Primarily, the Indian institutions which consume cardamom are, hotels, restaurants, bakeries, sweetmeat shops, and so on. Demand from this sector was increasing at the rate of 10% per annum and reached 1250 t in 2000 AD. A number of measures have been taken in India for widening the demand base. The Regional Research Laboratory (RRL), Trivandrum, Kerala State, The Central Food Technological Research Institute (CFTRI), Mysore, Karnataka State, have taken up studies for developing new cardamom-based products. The Indian Institute of Nutrition, Hyderabad, has conducted an investigation on the nutritional and medicinal values of cardamom. The Ayurveda College, Trivandrum, has carried out a study on the use of cardamom to develop *Ayurvedic* (the ancient Indian system of medicine) medicines for different common ailments. The Arya Vaidya Sala, the premier research and medical care institute in Kottakkal, Kerala State, has done pioneering work on the usefulness of cardamom-based soaps for good skin care (George and John, 1998).

The Spices Board of India, which comes under the administrative control of the Ministry of Commerce, Government of India, has been in contact with manufacturers of various food products to promote cardamom use. Some manufacturers have begun to use cardamom flavor in their products, while many have conducted tests to assess the suitability of cardamom oil as a flavoring agent in their manufactured products. As a result of all these efforts, a variety of end products using cardamom flavor have been launched in the market such as cardamom-flavored biscuits, toffee, flan, tea, and coffee powder, and cardamom-based concentrates (George and John, 1998).

A. Potential Applications

The future of any commodity depends on the present and potential uses. Since cardamom is a weak flavorant, it does not have adequate strength to displace a strong flavorant like vanilla. But, its use as a breath freshener finds widespread use in India. And it is preferred by many in place of the commercial chewing gum. Although cardamom seed has no chewing gum properties, because of its mild exciting taste and acceptable smell, the habit of chewing cardamom is spreading in many parts of India. Promotional efforts by the Spices Board of India have also tapped its potential as a substitute to smoking cigarettes and *Beedi* (the Indian version of the cigarette where tobacco is stuffed and rolled into ripened and cured *Kendu* leaves, a perennial tree growing in eastern India, whose dried and cured leaves are cut into small pieces to fill the tobacco leading to the finished product *Beedi*). In cola drinks, the aroma of cardamom is highly acceptable and the testing of consumer preference for cardamom-flavored cola in many cities in India has been very positive (Anon, 1996).

Medicinal value of cardamom has not been studied fully in any country. Only little work has been done in India. *Ayurveda* mentions the use of cardamom and has been found effective as a carminative, body massage oil and also as a suppressant of cold and cough, but more research needs to be carried out to understand the full potential of cardamom (Anon, 1952a, Sahadevan, 1965a).

B. Future Outlook

1. Research and Development

The most critical of the R&D efforts in cardamom production is to widen and enhance the genetic potential of the existing germplasms. And supportive crop management technology also plays a vital role. Unless a quantum

jump is attained in productivity, Indian cardamom cannot be competitive in world markets (Anon, 1988). Fertility management of cardamom-growing soils is a very important component of this task. As of now, prescriptive soil management aspects, especially inasmuch as cardamom nutrition is concerned, revolve around textbook knowledge. Almost the entire approach to fertility management in cardamom-growing soils is based on classic textbook knowledge, where empirical fertilizer recommendations generated from microplots are extrapolated to large-scale field conditions. These experimental microplots are nothing but artifacts and many of the recommendations, which emanate from such studies, when applied to large-scale plantations, turn out to be quite off the mark in reproducing quantifiable results. This often shatters the farmers' confidence. A significant departure is being made after concerted efforts of this author, who has developed an entirely new approach to soil testing and fertilizer management, based on nutrient buffering. The concept is now known, universally, as "The Nutrient Buffer Power Concept." A detailed discussion on the concept and its relevance in cardamom nutrition, especially with regard to potassium, which is required by cardamom in large quantities for high productivity, is given in this chapter. In India, in the state of Kerala, where cardamom is grown to a largest extent, it has been observed that fertilizer input can be significantly reduced by taking into consideration the buffer power of the nutrient under question. Experimental results of Nair *et al.* (1997) show that as against the routine soil testing and fertilizer recommendations, addition of K fertilizer, a crucial input in cardamom production, can be substantially reduced following the buffer power concept (Nair, 2002). There is an urgent need to extend the concept to other nutrients, possibly phosphorus and nitrogen as well as these are also crucial in cardamom production. Of these, phosphorus is more important in view of the fact that the soils of Kerala State, the home of cardamom, are lateritic and much of the applied phosphatic fertilizer, based on routine soil testing is rendered unavailable to the crop. It is in this context that the buffer power concept holds out much promise in cardamom farming. However, it must be emphasized that the success of a new approach, to a great extent, rests with the ingenuity of those applying it to suit the demands of a new situation. This principle is no exception to making "The Nutrient Buffer Power Concept" succeed in the case of cardamom production, as has been the case with other crops, such as black pepper, a perennial crop like cardamom, maize, rye, whiter clover, and so on (Nair *et al.*, 2002). The fact that cardamom is a perennial crop makes it all the more important because, unlike in an annual one, where a midcourse correction can be effected in the following season, in a perennial crop like cardamom the fertilizer regime has to be precise right from the beginning because cardamom grows upwards of 25 years. Unlike routine soil testing, the new approach calls for an accurate determination of the buffer power of the nutrient in question at the very start of the fertilizer regime. Once this is accomplished, the buffer power factor can be incorporated

into the computations with the routine soil test data and accurate fertilizer recommendations can be made on the basis of this new information. This implies that, in addition to obtaining routine soil test data, one also needs to know the buffer power. This author has obtained very encouraging results with the new concept in cardamom production in the State of Kerala, India, with regard to K fertilization, which is most crucial to cardamom productivity since K is the nutrient that the cardamom plant requires in the largest quantity. Hopefully, the new concept could successfully be extended to other important plant nutrients as well.

Cardamom being a shade-loving plant, its production physiology is different from other Zingiberous plants. And only little is known about these aspects. Productivity increase can be best achieved by genetic upgradation through new gene combinations and heterosis breeding and subsequent production of hybrid seeds. Production of genetically homozygous lines for heterosis breeding is thus an urgent need. Hence, an area of great importance is the production of haploids and diploids for hybrid seed production. This step itself can revolutionize cardamom production.

An intensive search is required to locate heat and drought tolerant lines. Heat and drought susceptibility are the most serious production constraints facing cardamom production in India. Once this is achieved, the incorporation of such resistance in elite genotypes can be achieved utilizing conventional breeding or the haploid–diploid hybrid system.

Resistance to biotic stress factors especially that of virus diseases is another equally important aspect that merits great attention by cardamom researchers. Survey of natural disease escapes in hotspot areas, their screening and evaluation has led to some *Katte* and rhizome rot resistant lines in the germplasm collection project of the Indian Institute of Spices Research, at Kozhikode, Kerala State, under the administrative control of the Indian Council of Agricultural Research, New Delhi. Some of these lines are high yielding as well. For the production of planting material, which is an important component of cardamom production, presently these lines can be made use of. At the same time, the agronomically superior lines have to subjected to molecular-breeding programs for the production of transgenics incorporating the *Katte* virus resistance either through coat protein mediated resistance or otherwise.

An important area of global importance is the emergence of organic farming and organically produced crops are in far greater demand than ever before. The spices form an excellent opportunity in this area and cardamom is no exception. A substantial quantum of research and developmental efforts has to go in to achieve the targets in this area. Another area that may yet emerge is the production of transgenic cardamom plants capable of surviving biotic and abiotic stresses. Cutting-edge technology in the area of cardamom production along these lines is nonexistent as of now, but future compulsions

would demand such efforts, although, at this stage, one cannot hazard a guess what the future holds out.

During the past decade and a half, world production and demand have increased parallelly, leaving very little as left-over production from the previous season. In fact, during this period, both production and demand enhanced by about 250%. It is also during this period that the cardamom industry grew manyfold, benefiting all those who are engaged in production, processing, and marketing. It is hazardous to predict the future of any nonessential agricultural produce with limited market and cardamom comes under this category, although, it is the second most prized spice in the world. However, it appears that cardamom has somewhat a bright future. But, any substantial increase in production by any cardamom-producing country in a short span of time might upset the supply–demand equation. Such a situation might lead to a steep price fall resulting in cardamom planters abandoning the crop. A situation almost akin to this was experienced by Guatemala in 1997–1998, when its production was at its peak, and the Middle East market for cardamom crashed due to the decline in oil boom.

In spite of the fact that both aroma and flavor of cardamom are acceptable in the manufacture of many foods, consumption in the developed world, primarily in the United States, Japan, European Union, Australia and New Zealand, and so on, is low. At present, the use of cardamom as raw material for the manufacture of processed foods, as cardamom oil and oleoresin will be in the range of 1500 t per annum in the developed world. This is primarily because no agency is making a concerted effort to boost cardamom use in these countries. As cardamom is produced in the developing world and the cardamom industry supports many small cardamom farers, it is desirable to have a concerted public relationship drive in cardamom use. There are a few reputed spice importers' associations, such as American Spice Trade Association (ASTA), European Spice Association (ESA), and All Nippon Spice Association (ANSA), which can be contacted for promotional purposes. Like in pimento and black pepper, where producers and importers have joined hands, an effort can also be imitated in the case of cardamom.

Other than in India, there is but scant cardamom consumption elsewhere. For sound development of agricultural industry, the best safeguard is the domestic market, since international markets can fluctuate from competing countries of production, as has been the case between India and Guatemala. Promoting cardamom consumption in both traditional and nontraditional countries of consumption must be initiated. The phenomenon of cheap Guatemalan cardamom flooding Indian market, both due to the liberalization of the economy, as well as due to clandestine import through the Nepalese border, has shattered Indian cardamom market. The lesson that

must be learnt from this episode is that unless farmers are enabled to produce competitively and diversify cardamom use, the future for cardamom will only be bleak.

XIII. LARGE CARDAMOM (*AMOMUM SUBULATUM ROXB.*)

Large cardamom is also known as Nepal cardamom (*Amomum subulatum Roxb.*) is a spice cultivated in the sub-Himalayan region of northeastern India, especially in Sikkim, since time immemorial. In the past, the aboriginal inhabitants of Sikkim, *Lepchas*, collected capsules of large cardamom from the natural forest but later on these forests passed into village ownership and the villages started cultivation of large cardamom. The presence of wild species, locally known as *churumpa*, and the variability within the cultivated species supports the view of its origin in Sikkim (Subba, 1984). Subsequently, the cultivation spread to northern Uttar Pradesh, northeastern states of India (Arunachal Pradesh, Mizoram, and Manipur), Nepal and Bhutan. Sikkim is the largest producer of large cardamom and the annual production in India is about 3500–4000 (t) of cured large cardamom. The average productivity is 100–150 kg ha^{-1} but in well-maintained plantations the productivity can go up to 1000–2000 kg ha^{-1}. Nepal and Bhutan are the other two countries cultivating this crop with an annual production of about 1500 (t). This spice is used in *Ayurvedic* medicines in India as mentioned by the great Indian Sage Medical Practitioner *Susruta* in the sixth century BC and this was also known to the Greeks and Romans as *Amomum* (Ridley, 1912). Large cardamom contains ca. 1.98–2.67% of volatile oil and is mainly used in flavoring food products (Gupta *et al.*, 1984). The seeds also possess certain medicinal properties, such as carminative, stomachic, diuretic, cardiac stimulant, antiemetic and are a remedy for throat and respiratory problems (Singh, 1978). As a marketable commodity, it is sold mainly in northern India. Over the past few years, large cardamom is also exported and in 1997–1998 India earned about US$3 million as export earnings, when the country exported 1784 t. Pakistan, Singapore, Hong Kong, Malaysia, United Kingdom, and the Middle East countries are the major importers of large cardamom.

A. Habit and Habitat

Amomum subulatum is a perennial herb, which belongs to the family Zingiberaceae under the order Scitaminae. The plant consists of subterranean rhizomes and several leafy aerial shoots and/or tillers. Number of such

rhizhomatous leafy shoots varies between 15 and 140 in a single plant or clump. Height of leafy shoot ranges from 1.7 to 2.6 m depending on the cultivar and possesses 9–13 leaves in each tiller. Leaves are distichous, simple, linear and lanceolate, glabrous on both sides with a prominent mid rib. Inflorescence is a condensed spike on a short peduncle. Flowers are bracteate, bisexual, zygomorphic, epigynous, and cuspinated. The yellowish perianth is differentiated into calyx, corolla, and anther crest. Each spike contains about 10–15 fruits (capsules) and rarely up to 20–25 capsules, depending on cultivars. Flowering season begins early at lower altitude with peak flowering during March–April, whereas it starts at higher altitudes in May with a peak during June–July. Harvesting begins during August–September at lower altitudes and in October–December at higher altitudes (Gupta and John, 1987). The fruit is a round and oval shaped capsule, trilocular with many seeds. Capsule wall is echinated, reddish brown to dark pink. Seeds are white when immature and become dark gray to black toward maturity. The capsules formed at the basal portion of spike are bigger and bolder than the others (Rao *et al.*, 1993).

Large cardamom is grown in cold and humid conditions under shade trees at altitudes varying from 800 to 2000 m amsl with an average precipitation of 3000–3500 mm, spread over about 200 days and the temperature ranging from 6°C in December–January to 30°C in June–July (Singh, 1988). Frost, hailstorm, and snowfall are the major deleterious factors affecting large cardamom. The crop grows well in moist, but well drained loose soil. The depth of soil varies from a few centimeters to several meters depending upon the topography and soil formation. Soil is acidic and rich in organic matter (Mukherji, 1968).

B. Cultivars

The commercially grown cultivars of large cardamom belong to the species *Amomum subulatum* Roxburgh. Out of the total 150 species of Amomum occurring in the tropics of the world, only about 8 species are considered to be native of eastern sub-Himalayan region, namely, *Amomum subulatum* Roxb., *Amomum costatum* Benth., *Amomum linguiformae* Benth., *Amomum pauciflorum* Baker., *Amomum corynostachyum* Baker., *Amomum dealbatum* Roxb. (*Amomum sericeum* Roxb.), *Amomum kingii* Roxb., and *Amomum aromaticum* Roxb. (Hooker, 1886). Later 18 species of *Amomum* were reported from the northeastern Himalayan regions (Anon, 1950). In the Indian subcontinent itself, there is another center of diversity in the Western Ghats region in the southwest India. Gamble (1925) has reported six species from this region.

There are mainly five cultivars of large cardamom, namely, *Ramsey*, *Sawney*, *Golsey*, *Varlangey* (*Bharlangey*), and *Bebo* (Gyatso *et al.*, 1980).

They are well known. Some other subcultivars of the above ones (*Ramnag*, *Ramla*, Madhusey, *Mongney*, and so on) are also seen in cultivation in small areas of Sikkim State in northeastern India. Another cultivar *Seremna* or *Lepbrakey* (a *Golsey* type) is also getting importance and is spreading to more areas at lower altitudes (Upadhyaya and Ghosh, 1983).

1. *Ramsey*

The name *Ramsey* was derived from two *Bhutia* (the language spoken in Bhutan, the northeastern India) words *Ram* meaning Mother and *Sey* meaning Gold (yellow color). This cultivar is well suited for higher altitudes, even above 1500 m on steep slopes. Grown up clumps of 8–10 years age group possess 60–140 tillers. The color of the tillers is maroon or maroonish green. Second fortnight of May is the peak flowering season. Capsules are small, average length is around 2.27 cm and 2.5-cm wide, with 30–35 capsules in a spike, each containing 16–30 seeds. The harvest is during October–November. Peak bearing capsules are noticed in alternate years, which is generally referred to as "Alternate Bearing," a phenomenon common in mango as well. This cultivar is more susceptible to the viral diseases *Foorkey* and *Chirke* especially if planted at lower altitudes. It occupies a major area under large cardamom in Sikkim and Darjeeling district of the State of West Bengal. Two strains of this cultivar, namely, *Kopringe* and *Garadey* from Darjeeling district having stripes on leaf sheath, are reported to be tolerant to *chirke* virus (Karibasappa *et al.*, 1987).

2. *Sawney*

This cultivar obtained its name from the Nepalese word *Sawan* which signifies the month of August by when it is ready for harvest and the cultivar grows well at low to midaltitudes. It is widely adaptable and can grow at high altitudes, even as high as 1300–1500 m. It is robust in nature and consists of 60–90 tillers in each clump. Its tillers are similar in color to that of *Ramsey.* Each productive tiller, on average, produces two spikes. Average length and diameter of a spike is 6 and 11 cm, respectively. Flowers are longer (6.23 mm) and yellow in color with pink veins. Second half of May is the peak flowering season (Rao *et al.*, 1993). Capsules are bigger and bold, and the number of seeds in each capsule are more (35) than in *Ramsey.* Harvest begins in September–October and may extend up to November in high altitude areas. This cultivar is susceptible to both *Chirke* and *Foorkey* viral diseases. Cultivars, such as *Red Sawney* and *Green Sawney*, derived their names from capsule color. *Mongney*, a strain found in south and west districts

of Sikkim is a nonrobust type with its small round capsules resembling mostly that of *Ramsey.*

3. *Golsey* (*Dzoungu Golsey*)

The name is derived from the Hindi (the widely spoken North Indian language) language and *Bhutia*, the Bhutan language, with the root *Gol* meaning round and *Sey* meaning Gold (yellow color). It is suitable for low altitudes, below 1300 m amsl especially in Dzongu area in North Sikkim. Plants are not robust like other cultivars and have 20–25 straight tillers with erect leaves. Alternate, prominent veins are extended to the edges of leaves (Biswas *et al.*, 1986). Unlike *Ramsey* and *Sawney*, tillers are green in color. Each productive tiller on an average produces two spikes. Flowers are bright yellow. On an average, each spike is 5.3-cm long and 9.5 cm in diameter and contains an average of seven capsules. Capsules are big and bold, 2.46-cm long and 3.92-cm wide and contain 60–62 seeds. This cultivar becomes ready for harvest in August–September. *Golsey* is tolerant to the two viral diseases *Chirke* and *Foorkey* and also the leaf streak diseases. The cultivar is known for its consistent performance, although not a heavy yielder. Many local cultivars are known in different locations such as *Ramnag* in North Sikkim. The word *Ramnag* can be split into its root *Ram* meaning mother and *Nag* meaning black, referring to the dark pink-colored capsules. *Seto-Golsey* is from west district of Sikkim with robust leafy stems or tillers and green capsules. *Madhusey* with elliptic and pink-colored capsules has robust leafy stem with sweet seeds compared to other cultivars (Rao *et al.*, 1993).

4. *Ramla*

The plants are tall and vigorous like *Ramsey* and have capsule characters like *Dzongu Golsey*, tillers are pink colored like *Ramsey* and *Sawney*. Cultivation is restricted to a few midaltitude plantations in North Sikkim. The capsules are dark pink with 25–38 seeds per capsule. *Ramla* appears to be natural hybrid between *Dzongu Golsey* and *Ramsey*. They are susceptible to *Chirke* and *Foorkey* viral diseases.

5. Varlangey

This cultivar grows in low, medium, and high altitude areas in South Regu (East Sikkim) and at high altitudes at Gotak (Kalimpong subdivision in Darjeeling district of the State of West Bengal). Its yield performance is

exceptionally high at higher altitude areas, that is, 1500 m amsl. It is a robust type and total tillers may range from 60 to 150. Color of tillers resembles that of *Ramsey*, that is, maroon to maroonish-green toward the collar zone. Girth of the tillers is more than that of *Ramsey*. Each productive tiller on an average produces almost three spikes with an average of 20 capsules/spike. Size of capsules is bigger and bold with 50–65 seeds. Harvest begins in the last week of October. This cultivar is also susceptible to both the viral diseases *Chirke* and *Foorkey*.

6. Bebo

This cultivar is grown in basar area of Arunachal Pradesh. The plant has unique features of rhizome and tillering. The rhizome rises above the ground level with roots penetrating deep into the soil, and the young tillers are covered under thick leafy sheath. It is supposed to be tolerant to *Foorkey* viral disease. The spikes have relatively long peduncle (10–15 cm) and the capsules are bold, red brown, or light brown; seeds contain low level of essential oil (2% v/w) (Dubey and Singh, 1990).

7. Seremna (*Sharmney* or Lepbrakey)

This cultivar is grown in small pocket at Hee-Gaon in west Sikkim at low altitude and is known for its high-yield potential. Plant features are almost similar to *Dzongu Golsey*, but the leaves are mostly drooping, hence, the name *Sharmney* (the root of the word *Sharm* in Hindi means modesty in a female with bowed head). Total tillers range from 30 to 49 and is not robust in nature. On an average, two to three spikes emerge from each productive tiller with an average of 10.5 capsules per spike, each having 65–70 seeds.

The comparative morphological characters of the four most important cultivars, namely, *Ramla*, *Ramsey*, *Sawney*, and *Golsey* are given in Tables LX and LXI.

C. Plant Propagation

Propagation of large cardamom is done through seeds, rhizomes (sucker multiplication), and tissue culture techniques. Cultivars suitable for specific areas, altitudes, agroclimatic conditions, and mother plant/clump of known performance are selected for collection of seed, rhizome, and vegetative bud.

Table LX
Growth Performance of *Ramla*, *Ramsey*, *Sawney*, and *Golsey* Cultivars of Large Cardamom (Average of 3 Years)

Plant characters	*Ramla*	*Ramsey*	*Sawney*	*Golsey*	CD at the rate of ($p = 0.05$)
Plant height (cm)	200.83	192.08	196.00	190.05	6.54
Tiller number per plant	59.08	42.00	40.50	39.80	12.67
Spike number per plant	40.25	36.00	35.00	30.00	4.70
Spike length (cm)	7.06	7.00	6.40	6.50	0.49
Spike breadth (cm)	8.60	7.00	6.00	7.20	1.47
Number of capsules per spike	16.00	12.00	13.00	14.00	1.12
Fresh capsule yield per plant (g)	375.00	185.00	190.00	216.00	14.00
Dry capsule yield per plant (g)	70.00	47.00	48.00	52.00	15.90

Note: CD, critical difference.

Table LXI
Capsule Characteristics of Different Cultivars of Large Cardamom (Average of 3 Years)

Capsule characteristics	*Ramla*	*Ramsey*	*Sawney*	*Golsey*	CD at the rate of $p = 0.05$
Fresh weight per capsule (g)	4.00	3.50	4.00	4.50	0.56
Dry weight per capsule (g)	0.90	0.75	0.85	1.00	0.14
Moisture (%)	13.00	14.00	13.00	15.00	1.54
Number of seeds per capsule	38.00	36.00	35.00	40.00	3.28
Volatile oil (%)	2.67	2.50	2.00	1.98	0.48

Note: CD, critical difference.

1. Nursery Practices

Propagation through seeds: Healthy plantation, free from viral disease, in particular, is selected for seed capsules. Normally gardens yielding 1000 kg ha^{-1} or more during the previous 3 years are selected. Higher spike bearing (reproductive) tillers per plant (bush), higher spike number and capsules which are bold, higher number of seeds per capsule, and so on, are some of the criteria based on which seed capsules are selected from the plot. Spikes are harvested at maturity and seed capsules are collected from the lowest two circles in the spike. After dehusking, the seeds are washed well in water to remove mucilage covering them, mixed with wood ash and dried

under shade. The dried seeds are then treated with 25% nitric acid for 10 min for early and higher percentage of germination (Gupta, 1989). The acid treated seeds are washed thoroughly in running water to remove the acid residue and are surface dried under shade. The seeds are sown immediately after such treatment.

2. Nursery Site Selection

An open area with gentle slope and having facility for irrigation is selected for nursery establishment. Large cardamom nursery is raised in two stages, namely, primary nursery and secondary nursery. Seedlings raised in the former by seeds are transplanted into the latter or into polybags.

a. Primary Nursery. Seeds are sown in September–October or early November (prewinter) or in Febraury–March (postwinter). September sowing results in quicker and better germination.

Seedbed is prepared in a well-drained area. Soil is cut to a depth of 30 cm and exposed to sunlight for a week. Bed of 15- to 25-cm height, 90-cm width, and of convenient length is prepared into which well decomposed cattle manure or compost is filled. Seeds at the rate of 100 g for a bed size of 1 m $\times$ 3 m are sown in furrows along the width and they are covered with a thin layer of soil. Space between furrows is maintained at 10 cm. After sowing beds are covered with thick mulch of paddy straw or dry grass and watered regularly to keep the seed bed moist. The seedbeds are examined about a month after sowing, and once germination starts after this period, the following operations are conducted.

1. Overhead shading using bamboo mat.
2. Mulch is removed from the bed, cut into small pieces, and spread over in between seed rows.
3. Seed beds are regularly watered and kept moist.

Once seedlings in the primary seedbed reach 3–4 leaf stage by February–March, when seeds are sown in September–October, or in April–May when seeds are sown in February–March, they are transplanted into polybags or into secondary nursery beds (Gupta, 1989).

b. Polybag Nursery. Top soil in virgin land/forest area rich in leaf mold is collected and mixed with well-decomposed cattle manure to get good potting mixture. A potting mixture of 5:1 topsoil:cattle manure is prepared and filled in polybags of 8 in. $\times$ 8 in. size with perforations at the base for drainage. Polybags are arranged under overhead shaded shed. Primary seedlings are transplanted in polybag (one seedling per polybag)

during February/March or April–May. Polybag seedlings are watered regularly with rose can to keep the soil moist. Care must be taken to cover the collar region or exposed roots of seedlings with thin layer of top soil, which help in better anchorage and tillering. Excessive watering must be avoided. Polybag seedlings attain a height of 30–40 cm with two to four tillers by July–August if transplanting is done in February–March. These seedlings are planted in the main plantation in July/August. The polybags are removed and seedlings with soil ball intact are planted. Sometimes the seedlings are maintained in the polybags until April the following year and planted in May–June (Anon, 1998).

c. Secondary Nursery. Seedlings from primary nursery are sometimes transplanted in beds. Beds of the size and nature similar to that of primary beds are prepared and seedlings of 3–4 leaf stage are transplanted in March/April/May, maintaining a spacing of 15 cm between seedlings. A layer of well-decomposed cattle manure is applied and incorporated in the soil. Watering is done at regular intervals to keep the soil moist. The entire secondary nursery is maintained under overhead shade (preferably black colored agro-net) and seedlings maintained for 10–12 months. Expected growth of seedling is about 45–60 cm in height with 5–10 tillers each and these are transplanted in June/July in the main field (Anon, 1998a).

d. Propagation Through Rhizome. High-yielding disease-free planting materials are selected for multiplication. Trenches 2-ft wide, 2-ft deep of convenient length are made across slopes. Trenches are filled with topsoil, leaf mold, and decomposed leaf litter. Rhizomes with one mature tiller and two young shoots or vegetative buds are planted at a spacing of 3 ft in the trenches in June/July. Thick mulching with dry leaf or grass is applied at the base of the rhizome and watering is done regularly to keep the soil moist. Once fresh vegetative buds appear, well-decomposed cattle manure is applied 1 ft around the rhizome and incorporated into the soil. Rhizome multiplication plot is maintained with 50% shade, either under shade trees or under agro shade net. When rhizomes are planted in June/July, about 15–20 tillers are produced from each of the rhizome within 6–10 months. Each such clump is split into units of two to three tillers and are used for planting in the main field in June/July or used for further multiplication (Anon, 1998a).

e. Micropropagation. Large cardamom can be multiplied on a large-scale through micropropagation. Protocols for micropropagation were developed by the Indian Institute of Spices Research (Nirmal Babu *et al.*, 1997a; Sajina *et al.*, 1997a). Auxiliary buds of 0.5–2 cm length from promising, virus-free mother plants are used as explants. The explants are thoroughly washed in clean running water and then in a detergent solution

and treated in 0.15% mercuric chloride solution for 2 min, and then passed through absolute alcohol for 30 s. These are cultured using the modified MS medium, solidified with agar, and with the following adjuvant.

Step 1: For initial bud development and its growth *in vitro* (culture period 6–8 weeks): kinetin 3–5 mg liter^{-1} + IBA 1–2 mg liter^{-1} + sucrose 20 g liter^{-1}

Step 2: For proliferation of the auxiliary bud rhizome (6–8 weeks): BAP 2 mg liter^{-1} + NAA 3–5 mg liter^{-1} + sucrose 20 g liter^{-1}

Step 3: For rooting and establishment of plantlets (6–8 weeks): IBA 1–2 mg liter^{-1} + KN 3–5 g liter^{-1} + sucrose 20 g liter^{-1}.

For complete details of the procedure please refer Nirmal Babu *et al.* (1997a) and Sajina *et al.* (1997b).

3. Plantation Management

a. Soil Condition, Preparation of Land and Shade Development. Large cardamom is grown in forest loamy soils having soil depths varying from a few centimeters to several meters. These soils are of medium fertility (Bhutia *et al.*, 1985; Biswas *et al.*, 1986). As the terrain is gentle to deep slope, chances of water stagnation are meager as water stagnation is very deleterious to the crop (Singh *et al.*, 1998). In general, large cardamom is cultivated on hill slopes and often in terraced lands, which were earlier put to the paddy crop, after raising adequate shade trees. Large cardamom is a shade-loving plant and grows tall under dense shade (60–70% of full day light interception) to light shade (about 30% full day light interception), (Singh *et al.*, 1989). The daylight intensity required for optimum growth of large cardamom ranges from 5000 to 20,000 Lux. Therefore, in virgin forests, it is necessary to clean undergrowth. Overhead shade regulation is essential in such areas having insufficient shade, planting shade saplings of different shade trees is done in June–July. The most commonly used shade trees are *Utis* (*Alnus nepalensis*, 600–2000 m amsl), *Panisaj* (*Terminalia myriocarpa*, 400–1000 m amsl), *Malato* (*Macaranga denticulata*, 670–1515 m amsl), and so on. It is advisable to plant more than one of the commonly used shade trees of the locality. In the case of fallow land, *Utis* is the first choice, as it is quick growing, capable of fixing atmospheric N, and has faster rates of nutrient recycling. Monoculture of *Utis* can fix as much as 29–117 kg/ha of atmospheric N. Yield of large cardamom has been found to increase as much as 2.2-fold under the canopy of *Utis*. Sharma and Ambasht (1988) have found Large cardamom based agro forestry under the influence of *Utis* more productive with faster rate of nutrient recycling. Depending on altitude, planting shade trees in rows at a distance of 9–10 m is ideal. While planting

the sapling, the course and direction of the sun and the slope of the hill must be taken into consideration. Usually the tree rows are run along the southwest direction inside the plantation.

b. Planting. For planting of large cardamom, pits are opened at spacing suitable for the variety or cultivar. In the case of robust varieties such as, *Sawney, Varlangey, Ramsey*, and so on, spacing followed is 150 cm × 150 cm while a spacing of 120 cm × 120 cm is used for *Golsey* (Dzongu). Pits are opened in April–May. The size of pits is usually 30 cm × 30 cm × 30 cm. After the first showers, pits are filled at least 15–20 days before planting with topsoil, decomposed cattle manure, compost or leaf mold along with 100 g rock phosphate. Ideally, planting is best done in June–August depending on rains. Staking is very essential to provide good anchorage.

c. Mulching. The plant base should be mulched with dried leaves, weeds, and trashes. Mulching must be done for fresh planting as well as existing ones in the month of October–November. This practice helps conserve soil moisture and also recycling plant nutrients.

D. Plant Nutrition

Most of the nutrients are removed by the vegetative growth in large cardamom and comparatively much less by capsules and spikes. Robust varieties like *Ramsey, Sawney*, and so on, remove twice the quantity of nutrients as compared to nonrobust ones like *Dzongu Golsey.* To produce 100 kg dry large cardamom, the robust types remove (in kg) 10.33 N, 1.95 P, 26.24 K, 19.10 Ca, and 11.9 Mg. The nonrobust type *Dzongu Golsey* removes, by comparison, 5.74 N, 0.99 P, 3.54 K, 9.18 Ca, and 5.86 Mg. Old leafy shoots removed during harvest are used as soil mulch. As large cardamom is grown under forest cover, manuring, and application of fertilizer is not usually practiced. Being a low-volume and less nutrient-exhausting crop, it has a degree of sustenance in terms of nutrient cycling. However, to obtain high yields, chemical fertilizer application is a must.

Application of NPK fertilizer in three splits, first in April–May after the first summer showers, followed by a second application in June and the last in September–October before monsoon ceases is recommended. Fertilizer must be applied in circular bands at a distance of 30–45 cm from the clump, with mild forking. A fertilizer schedule of 18.4 g, 6 g, and 18.6 g of N, P, and K respectively per clump produced large number of spikes per clump *Sawney*. However, *Golsey* did not respond to fertilizer application. Foliar application of urea (0.5–1%), DAP (0.5%), and muriate of potash (0.5–1%) in February, April, and October enhanced yield of *Ramsey*.

Large cardamom cultivation is an ecofriendly organic way of farming with minimal inputs, with least deleterious interactions with the soil system.

1. Weeding

About 51 species of weeds have been recorded in large cardamom plantations (Anon, 1984). Depending on the intensity of weed growth, two to three rounds of weeding are required per year. First weeding is done in February–April, before the first application of the fertilizer dose and just before flowering. Second and third round of weeding are done before harvest in August–September–October along with removal of dried leaves, unproductive tillers, and so on. The weeded materials are used for mulching.

2. Shade Regulation

Most of the shade tree species are deciduous in nature and hence frequent shade regulation is not required. However, during early years of shade establishment and also at 2- to 3-year intervals, the under growing side branches are cut to encourage straight growth and to allow the branches to spread at least 3–4 m above ground level so that moderate shade is maintained (Gupta, 1986)

3. Irrigation

When irrigated in summer months, yields are better as the cardamom plant is extremely susceptible to drought and water stress. Irrigation during November to March sustains good yield. In plantations, surface irrigation is generally resorted to.

4. Roguing and Gap Filling

One of the main reasons for poor productivity in large cardamom (yield as low as 50–150 kg ha^{-1}) is that most of the plantations have become senile and unproductive. The two viral diseases *Chirke* and *Foorkey* have been the cause for low yields. Hence, regular roguing of diseased and senile plants and filling the gaps with disease-free seedlings is a must to maintain productivity.

E. Crop Improvement

1. Flowering and Pollination

Large cardamom is essentially cross-pollinated and hence, insect pollination is the rule. Flower morphology is adapted for such a mode of pollination. Each spike consists of about 40–50 flowers, which open in an acropetal sequence over

a period of about 15–25 days. Flower opening commences between 3 and 4 A.M., anthers dehisce almost instantly, whereas stigma receptivity lasts 24 h. During rain-free days stigma receptivity lasts up to 36 h (Gupta and John, 1987).

Bumble bees (*Bombus* sp.) are the main pollinators, although a variety of honeybees and other insects pollinate flowers (Varma, 1987). The maximum foraging activity of the bees is between 6 and 7 A.M., and their size is compatible with the flower size, which facilitates good pollination. Rainy days are not conducive to good pollination.

2. Genetic Investigations

Karibasappa *et al.* (1989) carried out coefficient of variation investigations for mature tillers per clump, panicles per clump, and capsule–panicle ratio in *Sawney, Pink Golsey, Ramsey, Ramnag, and Madhusey*, and the investigations indicated high heritability coupled with genetic advance for characters such as length of mature tiller, panicles per clump, panicle weight, and capsule yield. The capsule yield was directly correlated with girth, panicle weight, panicle per clump, mature tillers, and capsule–panicle ratio. Correlation studies (Karibasappa *et al.*, 1989) also indicated that mature seed index, total soluble sugars (TSS) of seed mucilage and test weight of 1000 seeds were positively correlated with oleoresin content and negatively correlated with cineol content.

3. Clonal Selection

Exploration of germplasm collection of large cardamom has been carried out by Indian Cardamom Research Institute (ICRI), Regional Research Station, Gangtok in Sikkim State, and a gene bank of 180 accessions has been established at Pangthang. Rao *et al.* (1990) reported a promising selection of *Barlanga* cultivar from high altitudes, which has desirable attributes such as high ratio of mature tillers to productive spikes (1:3.6) and capsules having bold size (with 50–80 seeds per capsule). Based on a preliminary evaluation of four selections, namely, SBLC-5, SBLC-42, SBLC-42, and SBLC-47 A, having high-yield potential have been identified by ICRI, Regional Station at Gangtok. They are multiplied in large numbers using micropropagation technique and distributed among the farmers for cultivation.

F. Insect Pest Management

More than 22 insect pests are known to be associated with large cardamom and only a few of them cause substantial damage to the crop (Azad

Thakur and Sachan, 1987; Bhowmik, 1962). Following description pertains to some of the more important insect pests.

1. Leaf Caterpillar

Leaf eating caterpillar (*Artona chorista* Jordon, Lepidoptera: Zygaenidae), is a major pest of large cardamom in Sikkim and West Bengal State (Singh and Varadarasan, 1998). Its outbreak was recorded in 1978 in Sikkim where about 2000 acres of large cardamom plantations were severely defoliated (Subba, 1984). The leaf caterpillar was first recorded as *Clelea plumbiola* Hamson on large cardamom by Bhowmik (1962). *Artona chorista* occurs sporadically in epidemic form in Sikkim and West Bengal every year. Usually the pest incidence is observed in June–July and October–March. Severe damage was recorded in Lower Dzongu, Phodong, Ramthung Basit (North Sikkim), Soreng, Hee, Chako (West Sikkim), Kewizing (South Sikkim).

2. Nature and Extent of Damage

The leaf caterpillars are monophagous and highly host specific. The caterpillars are gregarious in nature and 60–200 caterpilars are found on each leaf and they feed on chlorophyll under leaf surface, leaving transparent epidermis, and veins (skletonization). The damaged portion becomes brownish which can easily be identified. Yield is adversely affected through defoliation. The area of a medium-sized cardamom leaf is 160–170 cm^2 and a mature larva consumes about 2.12 cm^2 each day (Singh and Varadarasan, 1998).

Management of the caterpillar infestation can be through mechanical, chemical, and biological means. Mechanical means are by physical collection and destruction. For chemical control, insecticides, such as Qinalphos or Endosulfan (0.05%), are effective. The danger of chemical control is that in the process of their use, they would also eliminate natural predators. As large cardamom is largely a naturally occurring vegetation, use of toxic insecticides is best avoided. For biological control, a species of predatory pentatomid bug has been found effective. It kills one to three larvae per day by sucking their body fluid.

3. Hairy Caterpillar

These are a group of defoliators which infest large cardamom. Severe infestation affects yield adversely. Among the hairy caterpillars, *Eupterote* sp. are the predominant ones, of which the major species are *Eupterote fabia*

Cramer and *Eupterote* sp. (Lepidoptera: Eupterotidae). The caterpillar infests during the monsoon period, from August onwards and the infestation can last up to December. *Eupterote fabia* and other species are sporadic and polyphagous and feed on leaves of cardamom causing defoliation. Sometimes *Eupterote fabia* causes severe defoliation.

The adult moth is large (10.8 cm across the wing) and yellow in color. The female moth lays eggs on the underside of leaves in clusters of 20–140 eggs. Hatching period lasts 19–21 days. Mature larva measures 7.4-cm long. Larval development is completed in 83–97 days and the adult emerges in 120–180 days (Azad Thakur and Sachan, 1987). Hairy caterpillar is a minor pest of large cardamom.

4. Aphids

Aphids do more damage as a vector rather than as a pest. They are the transmitters of the viruses, which cause *Chirke* and *Foorkey* diseases. The aphid population is recoded high during summer months at lower altitudes. The major species are following.

1. *Pentalonia nigronervosa* f. *caladii* (Groot) (Hemiptera: Aphididae)
2. *Micromyzus kalimpongensis* (Hemiptera: Aphididae)
3. *Rophalosiphum maidis* (Fitch) (Hemiptera: Aphididae)
4. *Rophalosiphum padi* (Lin.) (Hemiptera: Aphididae).

Pentalonia nigronervosa f. *caladii* and *Microzymous kalimpongensis* are known to be the vectors of *Foorkey* or yellow virus disease. The aphids colonize at the base (rhizome) of the clump and if population is more, they move to the aerial portion of the clump. Two to six aphids per tiller were recorded from the *Foorkey* infected plants during summer months. *P. nigronervosa* f. *caladii* is also reported as the vector of *Katte* viral disease in small cardamom. These aphids are dark brown in color, small and measure 1–1.15 mm in length. They remain mostly inside the soil close to rhizomes and suck the sap from the pseudostem. The alate (winged) and apterous (wingless) forms complete life cycle in 20–30 days.

Maize aphids, *R. maidis* and *R. padi* are reported on the lower surface of the leaves of large cardamom, congregating near the midrib and veins. These aphids are known to be the vector of another viral disease, mosaic streak, or *Chirke* (Raychaudhary and Chatterjee, 1965).

Removal and destruction of diseased plants is helpful in the control of further spread of the disease and in the reduction of aphid population. Spraying of 0.03% mimethoate or phosphomidon after removal of *Foorkey* and *Chirke* affected clumps in March–April gives adequate control of the aphids.

5. Shoot Fly

Shoot fly, *Merochlorops dimorphus* Cherian (Diptera: Chlopidae), recorded as a major pest of large cardamom damages young shoots. Low to moderate damage by shoot fly is recorded in large cardamom plantation in Sikkim and West Bengal. In the main field, more damage is recorded at higher altitudes than in lower altitudes. Another shoot fly, *Bradysia* sp. (Diptera: Sciaridae), has been reported by Kumar and Chaterjee (1993), to be damaging to large cardamom. As much as 54% of the new shoots are infected. Infestation leads to browning of the tip of the shoot which later completely dries up causing the symptom "dead heart." Single, pale glossy white larva bores the young shoots and feeds on the central core of pseudostem from the top to bottom resulting in the death of the shoot. The best management of the insect pest is to totally remove the infested young shoot at ground level and destroy the same.

6. Stem Borer (*Glypheterix* sp. Lepidoptera: Glyphiperidae)

It is a major and specific pest of large cardamom. Its infestation intensity varies and Azad Thakur and Sachan (1987) have reported 19% infestation in 1978–1979, but infestation can sometimes be far more severe. The infestation occurs from March to November. The larvae feed on the central portion of the shoot and as a result the terminal leaf of the plant gets dried up and this symptom is known as "dead heart," as in the case of the stem borer.

7. White Grubs (*Holotrichia* sp. Coleoptera: Melonthidae)

It is a polyphagous white grub-infesting roots and rhizomes of large cardamom. The infested plants show yellowing of leaves and withering symptoms. The grubs are white and "C" shaped with brown head. The incidence was recorded at Panthang (East Sikkim) and Kabi (North Sikkim) in September–December. This is a minor pest, hence, no control measures are adopted.

Leaf folding caterpillar (*Cotesia euthaliae* Bhatnagar. Hymenoptera: Braconidae) was recorded as larval parasitoid. It inflicts minor damage. The caterpillar pupates inside the folded leaf during winter. The mechanical control of collecting infested leaves along with the caterpillars is the best manner of controlling the pest.

8. Minor Pests

a. Mealy Bugs. These pests infect the underground rhizomes, feeding on roots and rhizomes, which causes yellowing of the plant in summer.

The pest is recorded at neem (East Sikkim), Tarku (South Sikkim), Chawang (North Sikkim), and Singling (West Sikkim) and usually found in March–October.

b. Leaf Thrips. The leaf thrip *Heliothrips haemorrhaidalis* (Thysanoptera: Thripidae) is a minor pest on leaves and infests the undersurface of leaves and they suck leaf sap. The damage is more on seedlings and recorded throughout the year. *Rhipiphorothrips cruentatus* Hood (Thripidae: Thysananoptera) is also reported as a minor pest of large cardamom on seedlings (Azad Thakur and Sachan, 1987). The leaf thrips population is more on the lower leaf surface compared to the upper surface. The infested leaves turn brown and wither gradually. For management, infested leaves are removed and destroyed. If infestation is severe, it can be controlled by spraying Monocrotophos or Quinalphos at 0.025% (Singh *et al.*, 1994).

c. Lacewing Bug. *Stephanitis typical* (Distant) (Hemiptera:Tigidae), is a minor sucking pest on large cardamom leaves. Severe infestation was recoded in 1997 in North Sikkim where about 1000 plants in an isolated patch were damaged. The infested area was open without any shade trees. The damage is recorded in the main field where shade was thin during pre and postmonsoon period. The infestation is recognizable even from a distance due to its grayish yellow feeding spots on the leaves. The bugs suck the sap on the lower surface of the leaves. In the case of severe infestation, plant growth and yield are adversely affected (Singh *et al.*, 1994).

d. Grasshoppers. They infest the plants in nurseries and the main field. Both nymphs and adults feed on leaves. The major species are *Mazarredia* sp. Bolivar (Tettigonidae) and *Chrotogonus* sp. (Acrididae).

e. Bagworm. *Acanthopsyche* sp. (Lepidoptera: Psychidae) is a minor pest. Its larvae cause small holes in the leaves. Damage is negligible, but the insect is seen in the plantation throughout the year.

f. Fruit Borer. The grub of *Scolytid beetle* (*Synoxy* sp.) makes a hole in the immature capsule and feeds on the seeds inside and pupates inside the capsule. The pest was recorded at Hee Gaon (West Sikkim).

g. Scale Insects. They colonize near the mid vein on the lower surface of the leaf. They suck the leaf sap, resulting in brownish spots on leaves. Minor infestation of scales was recorded in seedlings in Cardamom Nursery, Mallipayong (South Sikkim).

h. Rhizome Weevil. The weevil is brownish in colors and adult is about 1.5 cm, which feed on the rhizome by boring a tunnel into it. It was recorded at Kabi (North Sikkim) in the month of April.

i. Leaf Beetle. The adult, *Lema* sp. (Coleoptera: Chrysomelidae) is greenish brown in color and 8–10 mm in size which makes irregular holes in tender leaves.

j. Green Beetle. The green-colored beetle *Basilepta femorata* Jacoby (Coleoptera: Eumolpidae), is recorded in April and October on the leaves. The exact nature of damage is yet unknown. The grub is a major pest on *E. cardamomum* Maton (Varadarasan *et al.*, 1991). However, Azad Thakur and Sachan (1987) reported that adult beetles are very destructive as they nibble and eat away fresh leaf buds.

k. Nematodes. The dangerous root knot nematode, *Meloidogyne incognita*, is found to infect the seedlings in the nurseries and the plants in the main field causing considerable damage. The affected seedlings or plants show stunted growth, the leaves become narrow, and get a rosette form due to reduction in internodal length. The root system shows excessive branching with galls. Deep digging and exposure of the soil to sunlight (solarization) before preparation of nursery may reduce the nematode intensity. Use of the same site for nursery maintenance must be avoided for the infection to persist. Farmers are encouraged to change nursery every year and to raise the seedlings in polybags containing good potting mixture. This practice not only reduces nematode incidence, but also prevents movement of nematode through soil from one location to another.

9. Other Pests

Rodents, squirrels, and wild cats damage the fruits before harvest. Black cats, a nocturnal mammal, is known to cause heavy losses as they are voracious feeders of near mature capsules.

10. Storage Pest

A reddish brown caterpillar of cardamom bores into the capsule and feeds on the mucilagenous seed coat. However, the hard seeds are unaffected. The appearance of the capsules and the quality of seeds can be adversely affected.

G. Diseases

The large cardamom plant is susceptible to a number of diseases, which are mainly viral and fungal in origin. The viral diseases are the most severe and the fungal diseases are not the major problem. The two viral diseases causing major problems are *Chirke* and *Foorkey*. Among the fungal diseases, flower rot, clump rot, leaf streak, and wilt are known to cause damage to the plant and ultimately reduce crop yield.

1. The *Chirke* Disease

The disease is characterized by mosaic with pale streaks on the leaves. The streaks turn brown resulting in drying and withering of leaves and plants. The flowering in diseased plants is extensively reduced and only 1–5 flowers develop in one inflorescence, as against 16–20 in an inflorescence of healthy plants (Raychaudhary and Chatterjee, 1965) and by the end of the third year after planting the loss can be as much as 85%. The cultivar *Kopringe* is resistant to the *Chirke* disease, while the perennial weed, *Acorus calamus* L. was found to be highly susceptible (Raychaudhary and Ganguly, 1965). The disease is readily transmitted by mechanical sap inoculation and in the field it is spread by aphids, such as *Rhopalosiphum maidis* Fitch., within a short acquisition feeding period of 5 min.

Primary spread of the disease from one area to another is through infected rhizomes and further spread in the field by aphids (Raychaudhary and Chatterjee, 1965). Rapid serological method was developed to locate *Chirke* diseased plants under field conditions in the manner described by Bradley and Munro (Ganguly, 1966).

2. The *Foorkey* Disease

This disease is characterized by dwarf tillers with small, slightly curled pale green leaves. The virus (spherical particles of 37 μ in diameter; Ahlawat *et al.*, 1981a,b) induces remarkable reduction in size of leafy shoots and leaves of the infected plants and stimulates the proliferation of a large number of stunted shoots arising from the rhizome. The spikes/inflorescence are transformed into leafy vegetative parts and fruit formation is altogether suppressed. The diseased plants remain unproductive and gradually degenerate. The disease symptoms of the *Foorkey* disease appear both on seedlings and fully grown plants (Varma and Capoor, 1964). Unlike the *Chirke* disease, *Foorkey* disease is not transmitted through the sap but by aphids such as *Pentalonia nigronervosa* Cog. and *Micromyzus kalimpongensis* Basu

(Basu and Ganguly, 1968). The primary spread of the disease from one area to another is through the infected rhizomes and further spread within the plantation is through the aphids. Infected rhizomes can be killed by injecting Agroxone-40.

H. Management of the *Chirke* and *Foorkey* Diseases

The following methods are adopted which considerably minimize the infestation by the viruses (Chattopadhyay and Bhomik, 1965).

1. Regular roguing of diseased plants.
2. Diseased plants are uprooted and destroyed as and when detected.
3. The uprooted plants must be taken to an isolated place, chopped into small pieces, and buried in deep pits for quick decomposition.

1. Prophylactic Measures

1. Use of healthy and disease-free planting material, preferably seedlings.
2. Suckers as planting material from disease prevalent areas are avoided for replanting.
3. Raising nurseries in the vicinity of infected plantations must be avoided.

2. Leaf Streak Disease

It is a fungal disease caused by *Pestalotiopsis royenae* (D. Sacc) Steyaert. and is a serious disease among foliar diseases and is prevalent round the year. The disease symptom is the formation of numerous translucent streaks on young leaves along the veins. The infection starts from the emerging folded leaves and infected leaves eventually dry up causing loss of green part of the leaf, leading to, loss of photosynthetic surface, and results in yield loss. *Dzongu Golsey* is found to be more susceptible to leaf streak than other cultivars (Srivastava, 1991). Three rounds of 0.2% spray of copper oxychloride at fortnightly intervals, two schedules of such sprays per year, that is, February–March and September–October, can control the spread of the disease.

3. Flower Rot

This is a fungal disease caused by *Fusarium* and *Rhizoctonia* sp. The affected flowers turn dark brown and fail to develop into capsules, when infection takes place before or at the time of fertilization. If infection occurs

after flowering or during fruit set, the affected fruit or capsule loses color and odor (Srivastava, 1991). The disease can be managed by avoiding: (1) accumulation of leaf mass or mulch over the inflorescence or spike during monsoon and (2) soil spills over the spikes.

4. Wilt

A fungal disease caused by *Fusarium oxysporum* is prevalent in swampy and open areas. Early symptom is chlorosis of the older leaves commencing from the petiole region and progresses inwardly toward the young leaves. As the infection progresses, the pseudostems turn rotten, which blocks the vascular bundles and the pseudostem collapses as the infection progresses. Finally the plant dries up. Drenching 0.5% Dithane M-45 or Thiram would help check further spread of the disease in nurseries as well as in the main field. Planting in swampy or dry areas is best avoided.

I. Harvesting and Postharvest Technology

First crop comes to harvest about 2–3 years after planting of seedlings or suckers. However, stabilized yields are obtained only from the fourth year onwards and continues during the following 10–12 years. Harvest starts in August/September at low altitudes and continues until December at high altitudes. Usually harvesting is done in one round and hence, the harvested produce often contains capsules of varying maturity. Harvesting can be commenced when the seeds in the topmost capsules in the spike attain dark gray color. A special type of knife, locally known as *Elaichi chhuri* (meaning cardamom knife) is used for harvest. The stalk of the spike is cut close to the leafy shoot. After harvest, individual capsules are separated manually. Capsules after harvest are cured to reduce moisture content to 10–12%. The traditional curing known as the *Bhatti* curing system (direct heat drying) is followed. Large cardamom is also cured by Flue Pipe curing system, involving indirect heating system.

1. The *Bhatti* System

The local name for kiln is *Bhatti.* A *Bhatti* consists of a platform made of bamboo mats or wire mesh, laid over a four-walled structure made of stone pieces with a V-shaped opening in the front for feeding fire wood. Capsules are spread over the platform and are dried by direct heat generated from the burning of the firewood. To cure 100 kg of dry capsules about 70 kg of

firewood is required in this traditional kiln (Sundriyal *et al.*, 1994). Both green and dry wood can be used, and as a result, huge volume of smoke is generated that passes through cardamom (Singh, 1978). Depending on the thickness of the cardamom spread it takes 60–72 h to cure (John and Mathew, 1979). Color of cardamom cured in this system is dark brown to black. If smoke percolates through the cardamom spread, the original color is lost and the seeds have a smoky smell, which only will fetch a lower price in the market (Karibasappa, 1987).

2. Portable Curing Chamber

This is a prototype of the ‘‘Copra Dryer’’ (drying of dehusked coconut kernel) developed by the Central Plantation Crops Research Institute, Kasaragod, Kerala State, another research institute under the administrative umbrella of the Indian Council of Agricultural Research, New Delhi. The unit consists of an air heating chamber and a furnace cylinder with chimney. The whole unit is fitted in a detachable angular iron frame. The air-heating chamber is enclosed by asbestos sheets on all the four sides leaving the top open for drying. Some space is left below the walls for air to enter into the heating chamber. Fresh cardamom is spread on the platform (wire mesh size 3–5 cm) to a thickness of about 15- to 20-cm layer. Firewood is burnt inside the furnace cylinder. Air around the furnace gets heated up quickly and convected upwards and passes through the produce thereby drying it. The temperature of the heating chamber is regulated by the rate of burning of firewood and also by regulating the chimney valves. It takes about 20 h for curing of about 50 kg of raw samples (Annamalai *et al.*, 1988).

3. Flue Pipe Curing System

The Spices Board of India has introduced a novel system of curing called the ‘‘Flue Curing System’’ in place of the *Bhatti* system. The method has already been described earlier under the chapter on harvesting and processing of cardamom. The whole process of curing takes about 28–29 h. Cardamom capsules thus cured are immediately collected and rubbed in trays or processed in cardamom polishing machine to remove the tail (Anon, 1998). Clean produce is then packed in polyethylene-lined gunny bags and stored in wooden boxes. The cardamom cured in this manner gives, on average, 25% of the freshly harvested produce (John and Mathew, 1979). Cardamom dried in this method has the following advantages over those dried in the *Bhatti* system (Karibasappa, 1987).

1. Original pink color and sweet camphor aroma and flavor are retained.
2. It fetches better market price.
3. Curing expenses are low and also low firewood consumption.
4. Total curing takes only 28–29 h.
5. Uniform dryage is ensured.

J. Natural Convection Dryer

A dryer similar to the one described above has been designed by the Central Food Technological Research Institute, Mysore, Karnataka State (Joseph *et al.*, 1996). The dryer consists of a furnace, flue ducts, wire mesh tray for charging capsules and supporting structures. The furnace is fabricated using 8-mm thick MS sheets. A brick lining inside the furnace provides insulation. Flue ducts are made of 1.6 mm GI sheets, and the ducts are arranged in two tiers, one over the other, with sufficient space in between. Two crimped steel wire mesh trays with border are placed one over the other. Firewood is burnt to generate heat for drying. The hot flue gases passing through the ducts set up convection currents in the air between the duct wall and wire mesh trays. The convection currents pass upward through the mesh and the bed of cardamom capsules on the mesh are subjected to drying. The dryer has a thermal efficiency of 5.6, better than the conventional flue curing kilns. It can dry 300 kg large cardamom at a time for drying to a level of 10% moisture and the time required is 12 h. This method is much more efficient than the conventional drying system (Joseph *et al.*, 1996).

1. Gasifier Curing System

This is an upgradation of the *Bhatti* system and has been developed by the TATA (the leading industrial house of India with a great legacy behind it) Energy Research Institute (TERI) in Delhi. The solid fuel, firewood, through gasification and thermochemical reaction is converted into gaseous fuel by partial combustion. A mixture of producer gas consisting of carbon monoxide, carbon dioxide, methane, and elemental nitrogen is obtained, which is combustible and is used to burn. Through updraft type of biomass gasifier, air enters the gasifier from bottom and producer gas is taken out from top for curing cardamom. A prototype unit, which is fitted in the existing *Bhatti* curing system, has been successfully field tested in Sikkim and improved large cardamom with better appearance and more volatile oil content is obtained (Anon, 1998b).

The gasifier system is more advantageous than the traditional *Bhatti* system because the uncontrolled burning of firewood logs in the *Bhatti* system results in the loss of volatile oil; besides exposure to smoke imparts a smoked-smell to the volatile oil. There is also charring of capsules due to localized over heating. But, the controlled burning in a gasifier system of curing helps in retaining more of the volatile oil, accompanied with better quality without the smoky smell, due to clean burning of the gaseous fuel, and finally, the cured capsules retain the natural pink color of the harvested produce (Anon, 1998b).

K. Chemical Composition

Dried large cardamom seeds on analysis were found to contain the following.

Moisture: 8.5%
Protein: 6%
Volatile oil: 2.8%
Crude fiber: 22%
Starch: 43.2%
Ether extract: 5.3%
Alcohol extract: 7%
One hundred grams of dried seeds contain
Calcium: 666.6 mg
Magnesium: 412.5 mg
Phosphorus: 61 mg
Fluoride: 14.4 ppm.

The seeds contain the glycosides petunidin 3,5-diglucoside, leucocyanidin 3-*O*-β-D-glucopyranoside and subilin, an aurone glucoside. Cardamomum—a chalcone, alpinetin—a flavanone, are also reported to be found in the seeds (Shankaracharya *et al.*, 1990). The powdered seeds on steam distillation yield 1–3.5% of a dark brown, mobile essential oil. An investigation has shown that the volatile oil content is 2.44% in *Sawney*, 2.42% in Pink *Golsey*, 2.25% in *Ramnag*, and 1.66% in *Ramsey* (Shankaracharya *et al.*, 1990). The oil has the following properties: specific gravity (at 20°C): 0.9142, refractory index (at 26°C): 1.46; optical Rotation: –18° 3; acid value: 2.9; saponification value: 14.53; saponification value after acetylation 40.2. Large cardamom oil is characterized by flat cineol odor, harsh aroma, and inferior flavor as against the warm, spicy, aromatic odor of cardamom (Table LXII). The large cardamom oil is almost devoid of α-terpinyl acetate, and is rich in 1,8-cineole (Balakrishnan *et al.*, Gurudutt *et al.*, 1996).

Table LXII
Composition of Volatile Oil of Large Cardamom and Ordinary Cardamom

Constituents	Large cardamom (range in %)	True cardamom (range in %)
α-Terpinene	0.5–11.13	0.37–2.5
α-Pinene	2.0–3.11	1.10–13.00
β-Pinene	2.4–3.67	0.2–4.9
Sabinene	0.2–9.10	2.5–4.9
Camphene	0.44	0.02–0.13
v-Terpinene	0.2–16.2	0.04–11.2
Limonene	6.38–10.3	0.12–2.1
p-Cymene	0.20–0.30	0.40–0.70
1,8-cineole	63.3–75.27	23.4–51.30
Linalool	0.41	2.1–4.5
Geraniol	0.12	0.25–0.38
α-Terpineol	4.9–7.2	0.86–1.90
Terpinen-4-ol	1.42–2.0	0.14–15.3
Nerlidol	0.12–1.0	0.23–1.60
Nerlacetate	0.14	0.02–0.09
α-Terpinyl acetate	5.10	34.60–52.5
α-Bisabolene	1.3–3.6	0.07–0.83
β-Terpineol	0.8	0.70–2.10

Source: Shankaracharya *et al.* (1990), Balakrishnan *et al.* (1984).

L. Properties and Uses

Large cardamom is used as an ingredient as well as a flavoring agent with masala and curry powders; in flavoring dishes, cakes, and pastries; as a masticatory and for medicinal purposes. The seeds are used for chewing along with betel quid (beetle leaf, arecanut, lime, with or without tobacco). In the Gulf countries large cardamom is used as a cheaper substitute for spicing tea in place of ordinary cardamom. In the Indian systems of medicine, namely, *Ayurveda* and *Unani*, it is used as a preventive as well as a curative for throat trouble, congestion of lungs, inflammation of eyelids, digestive disorders, and even in the treatment of pulmonary tuberculosis (Kirtikar and Basu, 1952). The seeds are fragrant adjuncts for other stimulants, bitters, and purgatives. The seeds have a sharp and good taste and are a tonic for heart and liver. The pericarp is reported to be good for alleviating headache and heals stomatites (Anon, 1950). Decoction of the seeds is used as a gargle in afflictions of teeth and gums. With melon seeds they are used as a diuretic in the case of kidney stones. They promote elimination of bile and are useful in liver congestion. They are also used in the treatment of gonorrhea.

In large doses with quinine, they are used in neuralgia. The seed oil is applied to the eyes to prevent inflammation.

Cardamom can be directly used in the preparation of pickles, meat, and vegetable dishes and also in the preparation of *Pulao* a rice-based fragrant preparation, which is very popular in North Indian cuisine. Large cardamom also finds use in the industrial sector, to flavor toothpaste, sweets, soft drinks, toffees, flavored milk, and alcoholic beverages. The ripe fruits are eaten raw by the people of Sikkim and Darjeeling, which are considered a delicacy (Gyatso *et al.*, 1980).

M. Conclusions

Large cardamom is a crop of the northeastern Himalayan tracts, the largest producer being Sikkim in India. In South Asian countries, it is extensively used as a spice, and as a substitute for true cardamom in the Middle East regions. It is also important in tribal and indigenous medicine.

There is but meager information on research and development of this crop. Efforts are still to be initiated to evolve superior genotypes combining high yield and quality. A search for aroma quality is essential to locate lines of superior flavor and quality composition. More important is the management of diseases and pests, especially developing resistant or tolerant lines against the two serious viral diseases *Chirke* and *Foorkey*. The rich genetic diversity found in the center of its origin (Sikkim and the adjoining areas) has to be screened to locate natural resistance against pests and diseases, and also high yielders. A search for types adaptable to lower elevation will be a boon to take the cultivation of the crop to lower hills. A good tissue culture protocol for large cardamom is available and large-scale multiplication of some of the elite lines will provide disease-free superior planting material to the growers. Appropriate research back up is also needed to provide and popularize an efficient drying technology that will be suitable to the location and acceptable to small and medium-scale growers.

XIV. FALSE CARDAMOM

In addition to the true cardamom and the large cardamom, all the others which produce aromatic seeds, are clubbed together as false cardamom. They do not have much of commercial importance except in the case of *Aframomum corrorima* (*Amomum melegueta*, the Korarima cardamom or “grains of paradise”), which is cultivated on a small scale in some West African countries. But most of these false cardamoms are important locally

Table LXIII
Grades and Specifications for Cardamom

Grade designation	Trade name	Extraneous matter by mass (max. %)	Empty and malformed capsules by count (max. %)	Unclipped capsules by count (max. %)	Immature and shriveled capsules by weight (max. %)	Blacks and splits by count (max. %)	Size (DIA) of hole of the sieve on which retained (mm)	Mass minimum (g liter^{-1})	Color	General characteristics
Alleppey										
AG, green										
AGEB	Cardamom extra bold	Nil	2.0	Nil	2.0	Nil	7.0	435	Deep green	Kiln dried, three-cornered,
AGB	Cardamom bold	Nil	2.0	Nil	2.0	Nil	6.0	415	Green	and having a
AGS	Cardamom superior	Nil	3.0	Nil	5.0	Nil	5.0	385	or light	ribbed
AGS 1	Shipment green 1	Nil	5.0	Nil	7.0	10.0	4.0	350	green	appearence
AGS 2	Shipment green 2	Nil	5.0	Nil	7.0	12.0	4.0	320	Creamy	
AGL	Light green	Nil	–	Nil	–	15.0	3.5	260		
Coorg										
CG, green										
CGEB	Coorg extra bold	Nil	Nil	Nil	Nil	Nil	8.0	450	Golden	Global shape
CGB	Bold	Nil	2.0	Nil	3.0	Nil	7.5	435	to light	
CG 1	Superior	Nil	3.0	Nil	5.0	Nil	6.5	415	creamy	Skin ribbed or
CG 2	Superior coorg green or motta green	Nil	5.0	3.0	7.0	Nil	6.0	385	Creamy light greenish	smooth; the pedicles seperated
CG 3	Shipment	Nil	5.0	5.0	7.0	10.0	5.0	350	to greenish	
CG 4	Light	Nil	–	–	–	15.0	3.5	280	or brownish to brown	
Bleached or half bleached										
BL 1		Nil	Nil	Nil	Nil	Nil	8.5	340	Pale	Fully-developed
BL 2		Nil	Nil	Nil	Nil	Nil	7.0	340	creamy	capsules bleached,
BL 3		Nil	Nil	Nil	Nil	Nil	5.0	300	dull white	global or three cornered with ribbed or smooth skin

Bleached white										
BW 1	Mysore/Mangalore bleachable cardamom	Nil	1.0	Nil	Nil	Nil	7.0	460	White, light green or light gray	Fully-developed capsules suitable for bleaching
BW 2	Mysore/Mangalore bleachable cardamom	Nil	1.0	Nil	Nil	Nil	7.0	460		
BW 3	Mysore/Mangalore bleachable bulk cardamom clipped	Nil	2.0	Nil	Nil	Nil	4.3	435		
BW 4	Mysore/Mangalore bleachable bulk cardamom unclipped	Nil	2.0	Nil	Nil	Nil	4.3	435		
Mixed										
MEB	Mixed extra bold	–	2.0	–	2.0	Nil	7.0	435	–	
MB	Mixed bold	–	2.0	–	2.0	Nil	6.0	415	–	
MS	Mixed superior	–	3.0	–	5.0	Nil	5.0	385	–	Dried and mixed capsules of different varieties of *Elettaria cardamomum*
MS 1	Mixed shipment I	–	5.0	–	7.0	10.0	4.0	350	–	
MS 2	Mixed shipmentII	–	5.0	–	7.0	12.0	4.0	320	–	
ML	Mixed light	–	–	–	–	15.0	3.5	260	–	

[a]Notes: The determination of moisture content and total ash shall be made on the whole capsules.
[b]The determination of volatile oil shall be made on the seeds obtained after separation of the skin and decortication.

as spices and flavorents and as remedies for various ailments. Detailed studies on these species are lacking, although a few have been subjected to chemical analysis. This chapter deals with brief details on false cardamoms.

A. Elettaria

Sri Lankan wild cardamom *E. ensal* (Gaertn). Abheywickrme (*E. major* Thawaites)

This is the Sri Lankan wild cardamom. Morphologically similar to the true cardamom, but a more robust plant, bearing erect panicles and much elongated fruits (3–5 cm). Some controversy continues to exist regarding the taxonomic entity of this species. Burtt (1980), as well as Burtt and Smith (1983) did not treat this as a separate species, but included it under *E. cardamomum* only. Abheywickrama (1959) treated this as a separate species because of its more robust nature, distinctly different fruit size and, of course, the chemical composition is different. Burtt is of the opinion that these characters are not sufficient enough to separate the Sri Lankan wild cardamom into different species. The chemical analysis of the seeds showed that the two most important constituents of cardamom oil, 1,8-cineole and α-terpinyl acetate, are present only in traces in Sri Lankan wild cardamom. Bernhard *et al.* (1971) carried out comparative chemical analysis of the different cardamoms for the detection of constituents in the seeds, including Sri Lankan wild cardamom.

Malaysian and Indonesian *Elettaria*
Elettaria longituba (Ridl.) Holtt., in Gard. Bull. Sing., 13, 238, 1950.

Elettaria longituba is a perennial, vigorous herb endemic to Malaysia, and seems to be conspecific with *E. aquatilis*, reported from Sumatra. It is a large species, and its flowers appear singly or in long intervals, with only few flowers occurring per cincinnus. Flowering stolons (panicle) are 3- to 4-m long, and the anthers dehisce by pores without a hairy flap. Fruit is long, globose, or pyriform, smooth or slightly ribbed. There is no reported use for the plant or its fruit (Holttum, 1950).

Sakai and Nagamasu (2000) while studying the Zingiberaceae of Indonesia listed seven species of *Elettaria* from the region.

Elettaria rubida R. M. Sm. (described in *Botany Journal Linnaeus Society* 85, 66, 1982). It has a red inflorescence with orange flowers. The anther is ecristate, leaves are obovate, with an attenuated base.

Elettaria stolonifera (K. Schum.) Sakai and Nagamasu (described in *Edinburgh Journal of Botany*. 57, 227–243, 2000). The plants are 0.8- to 1.5-m tall, which trail on the ground. Inflorescence is 25- to 60-cm long,

flowers are white, anthers 3-mm long which dehisce in the upper half only. The anther crest is three-lobed, fruit unknown. *Elettaria kapitensis* Sakai and Nagamasu (described in *Edinburgh Journal of Botany*. 57, 227–243, 2000). The plant is about 0.7-m tall, inflorescence is 40- to 60-cm long, flowers white, calyx 17-mm long, corolla tube and calyx free above the ovary. The anthers dehisce throughout their length and the anther crest is about 2-mm long. Fruit unknown.

Elettaria surculosa (K. Schum.) B. L.Burt and R. M. Smith (described in *Notes of the Royal Botanical Garden, Edinburgh* 31, 312, 1972. It is synonymous with *Elettaria multiflora* R. M. Sm. described in *Notes of the Royal Botanical Garden, Edinburgh* 43, 452, 1986). Plant is about 1.2- to 2.0-m tall, inflorescence creeping on the ground up to 2-m long, white flowers and the anthers dehisce by small pores covered with a flap with long hairs up to 2-mm long. Fruit about 40 mm × 16 mm long, ellipsoid, sparsely pubescent, and reddish brown in color. *Elettaria linearicrista* Sakai and Nagamasu (described in *Edinburgh Journal of Botany*, 57, 227–243, 2000). The plant about 0.6- to 1.5-m tall, leaves narrowly oblong, inflorescence about 40-cm long, axis densely pubescent, somewhat erect, white flowers, anthers dehisce by longitudinally elongated pores at the upper middle of the thecae, fruit unknown.

Elettaria longpilosa Sakai and Nagamasu (described in *Edinburgh Journal of Botany*, 57, 227–243, 2000). The plant is 1- to 1.3-m tall, leaves densely pubescent on the lower surface, inflorescence about 50-cm long, creeping just below the ground, white flowers, anthers thecae dehiscing by a small pore just above midpoint, pore covered with a flap with long hairs, anther crest deeply three lobed, fruit unknown.

Elettaria brachycalyx Sakai and Nagamasu (described in *Edinburgh Journal of Botany*, 57, 227–243, 2000).

The plants are about 1.0-m tall, inflorescence about 60-cm long, white flowers, calyx about 6-mm long, fissured for two-third of its length, anther thecae which dehisces by pores covered with a flap of long hairs. Anther crest about 1-mm long, three-lobed, fruit unknown.

1. *Aframomum* sp.

Korarima cardamom [*Aframomum corrorima* (Braun). Syn., *Aframomum melegueta* (Roscoe) Schum (*Meleguetta* pepper, grains of paradise, or alligator pepper].

Korarima cardamom grows in wild and is also cultivated sporadically in Ethiopia, Nigeria, and the nearby regions, and the species is endemic to this region. It is a perennial aromatic herb with strong, fibrous, subterranean scaly rhizomes, and with a leafy stem of about 1- to 2-m high. The plants grow naturally at 1700–2000 m amsl in Ethiopia and in other tropical

West African countries. They flower in January to September, fruits mature 2–3 months after flowering. Propagated both by seeds and rhizome parts. No cultivation practices have been recorded. The dried products are usually of poor quality due to improper drying, that is, the case with many rural regions of Africa. Dried fruits are either sold in local markets or exported to other African countries and small quantities are exported to Saudi Arabia, Iran, and other Gulf countries. A rust disease caused by *Puccinia aframom* Hans food is common to this plant.

The seeds contain 1–2% essential oil, which has a typical odor and is called "nutmeg cardamom." Ajaiyeoba and Ekundayo (1999) carried out a gas chromatography–mass spectrography (GC-MS) investigation on hydrodistilled oil from samples purchased from the local market in Nigeria, which was found to contain 27 compounds of which α-humulene and β-caryophyllene made up the most, 82.6% of the oil.

Menut *et al.* (1991) compared the chemical composition of *Aframomum* and *Amomum* and came up with the following composition.

Type 1: *Aframomum angustifolium, Aframomum corrorima, Aframomum mala*, and *Aframomum muricatum* which contain roughly equal amounts of hydrocarbons and oxygen containing compounds.
Type 2: *Aframomum compactum, Aframomum kravanh*, and *Aframomum subulatum* which contain oxygen containing monoterpenes with 1,8-cineloe as the major constituent.
Type 3: *Amomum globosum* (from Thailand), *Amomum villosum*, *Amomum giganteum* which contain oxygen containing monoterpenes different from 1,8-cineloe.
Type 4: *Amomum globossum* (from China) which contains sesquiterpenes, α-humulene and farnasol.
Type 5: *Amomum ptychloimatum* which contains aliphatic compounds.

a. Uses. Korarima cardamom was once important in trade with Europe and part of the West African coast, which was then known as the "Grain Coast" (now Liberia). It was in demand by the local people as a spice and stimulating carminative and for a variety of other ailments. The fruit pulp around the seed is eaten especially before maturity and is chewed as a stimulant. The seeds are used as a spice in food to flavor all types of dishes in tropical African countries. They are also used to flavor tea and coffee, as in Arab counties and also in some special kinds of breads. In Ghana the seeds are used in enema preparations, and in Lagos and Sierre Leone they are used against fever and throat inflammations.

For external use the seeds are crushed and rubbed on the body as a counter irritant or applied as a paste to relieve headache, etc. (Dalziel, 1937). The whole plant decoction is taken as a febrifuge. The roots have a cardamom like taste and a decoction is used to relieve constipation. The roots are regarded as

a vermifuge against tapeworm, which infests humans through ill-cooked meat. The juice of the young leaves acts as a styptic (Dalziel, 1937). This was used in United Kingdom and United States in the preparation of medicines for cattle and also in the preparation of spiced wine (called hippocras), flavored with korarima cardamom, cinnamon, and ginger (Bentley and Trimen, 1880). The gastroprotective and antiulcer properties of an ethanol extract of korarima cardamom seeds in the case of rats using pyloric legation, hypothermic restraint stress, indomethacin (indometacin), cystamine, and narcotizing agents were investigated by Rafatullah *et al.* (1995). Galal (1996) studied the antimicrobial activity of 6-paradol and related-compounds present in korarima cardamom. These compounds were active against *Mycobacterium chelonei, Mycobacterium intracellulare, Mycobacterium smegonatis*, and *Mycobacterium xenopi*. Escoubas *et al.* (1995) have shown that extract of the seeds exhibited antifeedent activity against termites.

Aframomum daniellii Schum: A perennial herb occurring in West Africa, which grows to about 75 cm, having leaves 25- to 30-cm long. There are many red flowers in the inflorescence and the capsule is red and smooth, with smooth seeds, shining olive brown with white margin. Pulp of the seed is agreeably acidic and is eaten by the natives to refresh, which has turpentine like taste. It relieves thirst during fever. *Aframomum daniellii* inhibits the growth of several fungi and bacteria.

Aframomum granum–paradisi K. Schum (black *Amomum*): This occurs in Ghana, Gambia, Sierre Leone, and southern Nigeria. Seeds have shining surface, aromatic, and possess camphoraceous taste and flavor. The seeds are used by people together with shea butter (from *Vittellaria paradoxa* Gaertner, Sapotaceae) to make body pomade. The natives use the whole plant medicinally as in the case of *Aframomum corrorima*. Leaves are cooked with food to impart flavor. The plant has been wrongly identified earlier as grain of paradise.

Aframomum latifolium K. Schum (large or grape seeded *Amomum*): This is indigenous to Sierra-Leone. The seeds resemble grape stones, smooth, shining, and weakly aromatic. Ripe fruit is acidic and is eaten by the natives to refresh and is believed to be a good reliever of fatigue and is also used in fever (Dalziel, 1937). A decoction of the whole plant is mixed with the leaves of *Morinda lucida* (Rubiaceae) and used by the Susus tribe in daily bath to restore strength after fever and relieve fatigue.

Aframomum biauriculatum K. Schum: Chisowa *et al.* (1998) analyzed the rhizome of this species and identified 29 compounds in the rhizome oil and 17 compounds in the leaf oil. More than 58% of the leaf oil is β-pinere.

Aframomum sanguineum K. Schum: It is a native of West Africa. The seeds of this plant are used in cosmetics, to flavor tea and rice, and in traditional medicine to prevent throat infections and to treat stomach ache, dysentery, and snake bites. Among the most important constituents in the essential oil

of the seed, is 1,8-cineole, which has the maximum composition of more than 38% (Hari *et al.*, 1994).

2. *Amomum* sp.

a. Bengal Cardamom Amomum aromaticum Roxb (Jalpaiguri cardamom). This is a perennial herb, which grows to a height of about 1 m, indigenous to the northern West Bengal, Assam, Meghalaya, Sikkim, North Bihar, and northern West Bengal, extending to Nagaland and Uttar Pradesh. Leaves are oblong–lanceolate, pale yellow flowers, and rugose capsules. Seeds on steam distillation yield 1–2% of essential oil which has strong camphoraceous and cineol-like odor and taste and contain large quantities of cineole. Seeds are used as spice, which have medicinal properties, and are used in place of *Amomum subulatum*, the large cardamom.

b. Amomum dealbatum Roxb. A herbaceous perennial with large oblong-lanceolate leaves and globose short, peduncled spike, distributed in the Khasi hills of the eastern Himalaya. The leaves on distillation give an essential oil (0.018%), whose chief constituent is 1β-pinene and to a lesser extent α-pinene. The seeds are feebly aromatic in taste and odor and they are used as a substitute for large cardamom.

c. Amomum longiligulare Wu. A species, which occurs in Vietnam, and is used locally for medicinal purposes as well as to flavor food. It is used as medicine in dyspepsia, vomiting, diarrhea, and dysentery. Of the different constituents, the seed oil contains nearly 50% camphor (Dung and Thin, 1992).

d. Amomum tsao-ko Crevost Lemarim (Vietnam cardamom). A herb, 2- to 3-m high, with oblong-lanceolate leaves. Capsules are 2.5-cm long and oblong. The plant is cultivated in South China and Vietnam, especially in the forest regions of the Hoang Lien Son Mountain. The seeds contain 1–2% of essential oil, of which the main constituent (nearly 35%) is 1,8-cineole. Nearly 80% chemical constituents have been reported in the seed oil (Lizhu-Qiang *et al.*, 1998). The seeds are used as a spice in Vietnam and China as a substitute of true cardamom. It is also used as a local remedy for many ailments including dyspepsia, diarrhea, indigestion, and so on. Seven antioxidants have been reported to be found in the plant (Fang Jen and De, 1996).

e. Amomum krevanh. Indigenous to Thailand, it is often called Thai cardamom, where it is used in traditional medicine. Kamchonwongpaisan *et al.*

(1995) have isolated novel diterpene peroxide, the structure of which was elucidated by them. This compound exhibited potent activity against *Plasmodium falciparum*.

f. Amomum xanthiodis Wall (Tavoy cardamom). This plant is distributed in the forests of Indo-Burma, Malayan region. It is a perennial herb, leafy stem reaching about 1.5–2 m. Spikes are globose, few flowered, and shortly peduncled. Fruits (capsule) are oblong and pale brown. They are good at controlling diarrhea, dysentery, cramps, hiccups, nausea, splenitis, stomachache, anodyne, and also can be used as a carminative and sedative. Seeds contain a number of chemical constituents like D-camphor, linalool, nerolidol, and terpene and are effective in relieving painful urination and regulating bowel movements. For this, powdered seed mixed with butter is administered. The Chinese and Burmese use this as an important condiment (Kirtikar and Basu, 1952).

g. Amomum compactum Soland (round cardamom) syn. Amomum kepulaga Sprague and Burkill. Round cardamom, also known as Siam cardamom, is reported to be antitoxic, antiemetic, carminative, and stomachic. In China, it is folk remedy for ague, cachexia, cancer, catarrah, cold, coughs, cramps, dyspepsia, gout, heartburn, nausea, heptosis, ophthalmic, rheumatism, and vomiting. It is rarely used alone, more frequently in combination with other plant products. Mixed with fresh egg yolk, it is used in parturition. Elsewhere the plant is used in folk remedies for indurations of liver and uterus and against cancer (Perry and Metzger, 1980).

h. Amomum constalum Benth. Endemic to the Eastern Himalayan forests: It is a perennial herb with stout leafy stem 1.5- to 2-m long. Spikes are peduncled, 5–7.5 cm and seeds are aromatic. In Chinese medicine the seeds are employed for ailments of the stomach and for asthma, pulmonary afflictions, and general debility. Tribals use the seeds to relieve stomach ache.

i.* Amomum pavieanum *Pierre and Gagnep. It is endemic to Southeast Asia. An infusion of this plant is used in the treatment of diarrhea and general debility following certain dysenteries. The rhizome is used as a seasoning agent in the eastern and southern parts of Thailand (Perry and Metzger, 1980). The oil yield (0.23% v/w) is colorless having an anise-like odor (Scheffer *et al.*, 1988). Gas chromatagraphic analysis has identified 41 compounds in the rhizome oil. The dominant (91.6%) compound of the oil is methylchavicol. Only four other components amounted to more than 1%, namely, α-pinene, camphene, β-pinene, and camphor. The composition of *Amomum pavieanum* is quite distinct from other species, by the absence of 1,8-cineole as the dominant component. It seems, there is no other

Amomum sp. having oil composition resembling that of *Amomum pavieanum* (Scheffer *et al.*, 1988).

j. Amomum acre Valeton. This is an Indonesian species mainly found in Sulawesi region. The fruits and inner part of the petioles are used for pickling, which are often pickled in vinegar and subsequently used as a spice and as a flavorant. Very young stem is used directly. The plant itself is poorly understood.Two forms have been distinguished, namely, *Rombo* and *Kautopi* (de Guzman and Siemonsma, 1999). There is only scarce information on the chemical composition of the seed oil etc.

k. Amomum ochreum Ridley. This occurs in Peninsular Malaysia. The seeds of this species are used locally as a substitute for cardamom. The plant is 3- to 4-m tall, produces inflorescences (spikes) from the base, flowers having obovate, three-lobed labellum, orange-yellow with red veins and spots, anther appendage transversely oblong, and faintly red spotted (de Guzman and Siemonsma, 1999).

l. Amomum testaceum Ridley. This occurs in Thailand, Vietnam, Peninsular Malaysia, and Borneo and is only occasionally cultivated. Seeds are aromatic and locally used like true cardamom.

The plant is a rhizomatous herb with leafy shoots about 3-m tall, inflorescence an oblongoid spike emerging from the rhizome, flowers have obovate labellum, white with a broad dull yellow patch toward the apex and paler yellow median band flanked by purple lines, stamens with 8-mm long filament, and three-lobed anther appendage (de Guzman and Siemonsma, 1999). Fruits slightly ribbed and pinkish, slightly hairy. Seeds are brown, aril thin, and aromatic, and their chemical composition is unknown.

m. Amomum xanthophlebium Baker (Syn. Amomum stenoglossum Baker). This occurs in Peninsular Malaysia and Borneo. Flowers are used for flavoring curries. The plant is a rhizomatous herb, leaf stem up to 4- to 5-m tall, inflorescence is ellipsoidal spikes arising from the rhizome, flowers have obovate labellum, edges are crinkled, white suffused with red stripes and spots. Fruit is obovoid, smooth suppressed silky hairy (de Guzman and Siemonsma, 1999). Flowers are used by locals to flavor various dishes. Seeds are used by tribals in local medicinal preparations. There is no information on chemical composition.

The following species of Amomum occur in Western Ghat forests of southern India: *Amomum involucratum* Benth; *Amomum hypoleucum* Thw; *Amomum cannicarpum* (Wight) Benth. ex Baker; *Amomum muricatum* Beddome; *Amomum ghaticum* Bhatt; *Amomum masticatorium* Thwaites and *Amomum pterocarpum* Thwaites. There is no information about their use in

local or tribal medicine. No study has been undertaken with regard to the chemical composition of the seeds of these species.

XV. SPECIFICATION FOR CARDAMOM

A. Requirements

1. Cardamom with Capsules

The cardamoms shall be nearly ripe fruits of *Elettaria cardamomum* (L.) Maton in the form of capsules, which have been dried. The capsules will be of color ranging from light green to brown, cream, and white. Global in size or three cornered having a ribbed appearance. The capsules may be clipped and their pedicels removed. The capsules shall be well formed and with sound cardamom seeds inside. The capsules may also be bleached. The cardamoms may be graded on the basis of color, clipping, size, mass per liter, bleaching or otherwise, proportions of extraneous matter, or place of origin.

a. The Cardamom Seeds. Capsules may also be decorticated and the separated seeds packed for trade purposes. The cardamom seeds may be graded on the basis of mass per liter and extraneous matter.

b. Taste and Aroma or Flavor. The taste and aroma or flavor of cardamom capsules and seeds shall be characteristic and fresh. The material shall be free from foreign taste and aroma or flavor, including rancidity and mustiness. Freedom from moulds, insects etc. Cardamom capsules and seeds shall be free from visible moulds and insect infestation.

c. Mass per liter. The mass of cardamom capsules and seeds shall be determined in accordance with the method given in 4 of Indian Standards: 1797–1973.

Moisture content: The moisture content in all grades of cardamom except the grade "Bleached" or "Half Bleached" shall not exceed 10% when determined in accordance with the method given in 10 of Indian Standards 1797–1973. The moisture content in the grade bleached or half bleached shall not exceed 13% when determined by the same method.

d. Volatile Oil Content. The volatile oil content of different grades of cardamom capsules shall not be less than 3.5% on capsule basis and in the case of seed grades it shall not be less than 4% on the seed basis when

determined in accordance with the method given in 15 of Indian Standards 1797–1973.

2. Extraneous Matter

The proportion of calyx pieces, stalk bits, and other extraneous matter in cardamom in capsules and seeds shall not be more than 5% and 2% by mass, respectively, when determined in accordance with the method given in 5 of Indian Standards 1797–1973.

a. Empty and Malformed Capsules. The proportion of shriveled capsules, which are not fully developed, shall not be more than 7% by mass and shall be determined after separating them in accordance with the method given in 5 of Indian Standards 1797–1973.

b. Blacks and Splits. Blacks include capsules having visible blackish to black color and splits include those capsules which are open at corners for more than half the length. The proportion of blacks and splits shall not be more than 15% by count. For this purpose, 100 capsules shall be taken from the sample and the number of blacks and splits separated and counted.

c. Light Seeds. The proportion of light seeds in cardamom seeds shall not be more than 5% by mass, when separated in accordance with the method given in 5 of Indian Standards 1797–1973. Light seeds shall include seeds, which are brown or red in color broken or immature and shriveled.

d. Grades. The cardamoms in capsules and seeds may also be graded before packing. There shall be 25 grades of cardamom with capsules of three cardamom seeds. The designations of the grades and their requirements are given in the following table (Table LXIV).

3. Packing and Marking

a. Packing

Capsules: Cardamoms with capsules shall be packed in clean, sound, and dry tinplate containers or wooden cases suitably lined with polythene or waterproof paper or kraft paper or in new jute bags lined with polythene waterproof paper.

Seeds: Cardamom seeds shall be packed in clean and dry tinplate containers or wooden cases lined with polyethylene or waterproof paper or kraft paper.

Table LXIV
Grade Designations of Cardamom Seeds and their Requirements

Grade designation	Trade name	Extraneous matter by mass (%)	Light seeds by mass (%)	Mass (g liter^{-1} min^{-1})	General characteristics
CS1	Prime	0.5	3.0	675	Decorticated and dry seeds of any variety of *Elettaria cardamomum*
CS2	Shipment	1.0	5.0	660	
CS3	Brokens	2.0	–	–	

b. Marking. The following particulars shall be marked or labeled on each container.

1. Name of the material and the trade name or brand name, if any
2. Name and address of the manufacturer or the packer
3. Batch or code number
4. Net mass in metric units
5. Grade of the material (if graded)
6. Country of origin.

Sampling: Representative samples of the material shall be drawn and tested for conformity to this specification as prescribed in 3 of the Indian Standards 1797–1973.

4. Specification for Large Cardamom

Scope: This standard specifies the requirements and methods of sampling and test for large cardamom, in capsules and seeds of *Amomum subulatum* Roxb., and other related species.

Reference:

The Indian Standards (IS) listed below are necessary adjuncts to this standard.
IS No:
1070: 1977 Title
1797: 1985 Water of general laboratory use
13,145: 1991 Method of sampling for spices and condiments.

5. Requirements

a. Description

Large cardamom in capsules: Large cardamom are the dried nearly ripe fruits of *Amomum subulatum* Roxb., and other related species. The capsules shall be of the color ranging from brown to pink, ovoid, and more or less triangular shaped having ribbed appearance. The capsules may be clipped, and their pedicels removed. The capsules shall be well formed with sound seeds inside.

Large cardamom seeds: The cardamom capsules may also be decorticated and the seeds separately packed for trade purpose.

Odor and taste: The odor and taste of large cardamom capsules and seeds shall be characteristic and fresh. They shall be free from foreign odor and taste.

Freedom from insects, moulds: Large cardamom capsules and seeds shall be free from living insects and mould and shall be practically free from dead insects and rodent contamination visible to the naked eye with such magnification as may be necessary. If the magnification exceeds 10×, this fact shall be stated in the test report.

Extraneous matter: Large cardamom capsules and seeds shall be free from visible dirt or dust. The proportion of pieces of calyx and stalk and other extraneous matter shall not be more than 5% when determined by the method specified in 4 of IS 1797: 1985.

Empty and shriveled capsules: The proportion of immature and shriveled capsules shall not be more than 7% when determined after separating them in accordance with the method given in 4 of IS 1797: 1985.

Light seeds: The proportion of light seeds in large cardamom seeds shall not exceed 5% when determined in accordance with the method given in 4 of IS 1997: 1985.

Mass per liter: The mass of large cardamom capsules and seeds contained shall be determined according to the method given in 3 of IS 1797: 1985.

Chemical requirements: The Large cardamom capsules and seeds shall also comply with the requirements given in Table LXIII.

b. Packing. Cardamom capsules shall be packed in clean, sound, and dry tinplate containers or in suitably lined wooden cases or in suitably lined new jute bags. Lining materials may be, for example, waterproof paper, kraft paper, or plastic material.

Cardamom seeds shall be packed in clean and dry tinplate containers, or wooden cases suitably lined, for example, water proof paper, kraft paper, or plastic material of food grade quality.

Table LXV
Chemical Requirements

Serial no.	Characteristics	Requirement	Methods of test Reference to CI of IS 1797:1985
1	Moisture, content percent (m m^{-1}), max.	12.0	9
2	Volatile oil content (ml/100 g) on dry basis, minimum	1.0	15

Note: "pure Chemicals" mean chemicals that do not contain impurities which affect the results and analysis.

c. Marking. The following particulars shall be marked or labeled on each container.

1. Name of the material, trade name or brand name, if any
2. Name and address of the manufacturer or packer
3. Batch or code number
4. Net mass
5. Year of harvest
6. Sampling.

Representative samples of large cardamom in capsules and seeds shall be drawn by the method prescribed in IS 13,145: 1991.

d. Tests. Tests shall be carried out in accordance with 3.4, 3.6, 3.7, 3.8, and 3.9 and column 4 the following table (Table LXV).

e. Quality of Reagents. Unless specified otherwise, pure chemicals and distilled water shall be employed in tests.

ACKNOWLEDGMENTS

With utmost devotion and respect I dedicate this chapter to my late parents, my father, Kuniyeri Pookkalam Kannan Nair, and my mother, Kodoth Padinhareveetil Narayani Amma, both of whom left me an orphan at a very young age, but whose blessings made me what I am today. To my wife Pankajam, our children Kannan, Sreedevi, Arvind, and Heera, and Cheri, our German shepherd, for their love that inspired me to compile this most exhaustive chapter under very trying circumstances.

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Index

J

K

L

M

N